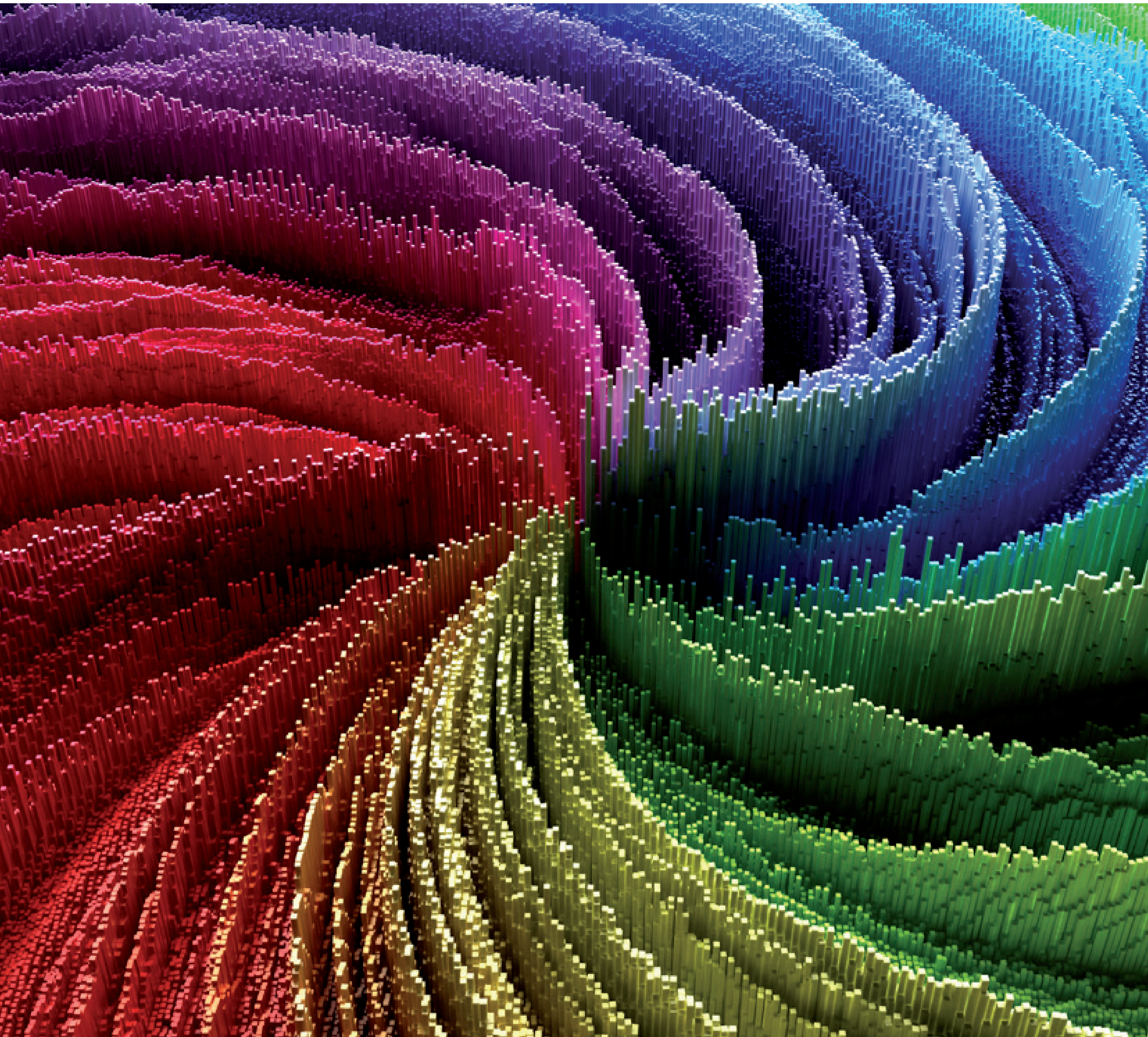
Europäisches Patentamt
European Patent Office
Office européen des brevets

Patents and additive manufacturing

Trends in 3D printing technologies



Foreword

Dear readers,

The vast stores of data held by the EPO are one of our organisation's key strengths. When carrying out a search or examination for a patent application, EPO examiners have access to over 1.5 billion technical records from 182 databases. Not only is this wealth of patent information a defining element of high-quality patents, it is also the key to generating cutting-edge insights and business intelligence.

The Internet of Things, artificial intelligence, big data and cloud computing have triggered a Fourth Industrial Revolution in nearly all sectors of the economy. Additive manufacturing (AM) – more commonly known as 3D printing – is one of the key drivers of this revolution. The EPO's first landscaping study on patents and AM technologies offers unique insights into emerging trends in this fast-growing field.

AM may potentially redesign entire industry value chains in large swathes of the global manufacturing industry. It is also a fascinating technology, drawing on the most advanced digital technologies to craft objects of unmatched complexity in an ever-growing variety of materials – ranging from concrete to living cells. This study reveals a recent surge in AM innovation in countless industry areas, calling for greater collaboration between the impacted sectors.

Alongside the US, Europe has built up a strong position as a global hub for AM technologies in recent years. This is clearly reflected in the list of the EPO's top 25 AM applicants, with European inventors submitting almost 50% of all AM patent applications filed with the EPO in the past decade. Innovation in AM involves major European players from a wide range of industries, as well as a large population of small businesses and universities.

These findings confirm the bigger picture that emerges from our analysis of the EPO's annual patent statistics in recent years, namely that a diverse technology portfolio is helping to make Europe more competitive. In relation to AM technologies, this study highlights Europe's innovative strength in a game-changing domain.

António Campinos
President, European Patent Office

Contents

List of abbreviations

AM	Additive manufacturing. Process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative methodologies (ISO/ASTM 52900 standard definition). Historical terms include additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, solid freeform fabrication and freeform fabrication.
3D printing	Fabrication of objects through the deposition of a material using a print head, nozzle or other printer technology (ISO/ASTM 52900 standard definition). Term often used in a non-technical context synonymously with additive manufacturing. Previously associated in particular with machines that are low-end in price and/or overall capability.
CAD	Computer-aided design. Use of computers to design real or virtual objects.
CAGR	Compound annual growth rate
CAM	Computer-aided manufacturing. Typically refers to systems that use surface data to drive CNC machines, such as digitally driven mills and lathes, to produce parts, moulds and dies.
CNC	Computer-numerical control. Computer-controlled machines include mills, lathes and flame cutters.
FDA	US Food and Drug Administration
FDM	Fused deposition modeling. Trade name used by Stratasys for the company's material extrusion technology.
EPO	European Patent Office
Espacenet	Free online service from the European Patent Office for searching patents and patent applications. Includes more than 120 million documents.
GDP	Gross domestic product
IPC	International Patent Classification
IPR	Intellectual property rights
ISO	International Organization for Standardization. International standard-setting body composed of representatives from various national standards organisations.
PC	Polycarbonate
PLA	Polyactic acid or polyactide
PRO	Public research organisation
R&D	Research and development
RTA	Revealed technological advantage. Provides an indication of a given economy's relative specialisation in various technology domains.
SiC	Silicon carbide
SLA	Stereolithography apparatus
SLS	Selective laser sintering. Trade name used by 3D Systems for the company's polymer powder bed fusion technology.
SMP	Shape memory polymers

List of countries

Contracting states to the European Patent Convention (EPC)

AL	Albania	**IT**	Italy
AT	Austria	**LI**	Liechtenstein
BE	Belgium	**LT**	Lithuania
BG	Bulgaria	**LU**	Luxembourg
CH	Switzerland	**LV**	Latvia
CY	Cyprus	**MC**	Monaco
CZ	Czech Republic	**MK**	North Macedonia
DE	Germany	**MT**	Malta
DK	Denmark	**NL**	Netherlands
EE	Estonia	**NO**	Norway
ES	Spain	**PL**	Poland
FI	Finland	**PT**	Portugal
FR	France	**RO**	Romania
GB	United Kingdom	**RS**	Serbia
GR	Greece	**SE**	Sweden
HR	Croatia	**SI**	Slovenia
HU	Hungary	**SK**	Slovakia
IE	Ireland	**SM**	San Marino
IS	Iceland	**TR**	Turkey

Non-EPC countries

AU	Australia
CA	Canada
CN	P.R. China
IL	Israel
JP	Japan
KR	R. Korea
SA	Saudi Arabia
TW	Chinese Taipei (Taiwan)
US	United States of America

List of tables and figures

Tables

Figures

Executive summary

Aim of the study

Additive manufacturing (AM), more commonly known as 3D printing, is radically changing the way in which products are made. Manufactured objects have been produced for centuries using the same conventional processes, such as forging, casting and machining. AM offers a new approach, whereby thin layers of material are deposited one on top of another until a complete three-dimensional object is formed. This new approach is compatible with a large variety of materials, from metals to living cells, and has a wide range of potential industrial applications.

AM is primarily a digital technology, and as such one of the key drivers of the Fourth Industrial Revolution (EPO, 2017). 3D printed objects are the physical avatars of digital models that allow for highly sophisticated shapes or geometries. These models can be instantly diffused at virtually no cost, enabling the local fabrication of small volumes. They can also be modified, allowing in turn for the mass-customisation of 3D printed objects.

As the technology matures, it is estimated that AM could capture 5% or more of the global EUR 10.7 trillion (USD 12 trillion) manufacturing industry. While originally used for prototyping, its value is now seen in making industrial manufacturing more efficient, by using fewer resources while making it easier, cheaper and faster to build complex shapes and custom one-off designs. AM has the potential to redesign entire industry value chains, and will oblige companies to rethink their distribution models and to adapt to new forms of competition, while facing the challenge of creating appropriate legal frameworks to safeguard competition.

This study provides a comprehensive picture of current trends and emerging leaders in AM technologies. Drawing on the latest patent information from the European Patent Office (EPO), it gives a unique insight into AM innovation, and informs users of the patent system and policy-makers about AM's impact on industry.

About patent information

Patents are exclusive rights that are granted only for technologies that are new, inventive and industrially applicable. High-quality patents are assets for inventors because they can help attract investment, secure licensing deals and provide market exclusivity. Patents are not secret. In exchange for these exclusive rights, all patent applications are published, revealing the technical details of the inventions they describe.

Patent databases therefore contain the latest technical information, much of which cannot be found in any other source, and which anyone can use for their own research purposes. The EPO's free Espacenet database contains more than 120 million documents from over 100 countries, and comes with a machine translation tool in 32 languages.

This patent information provides early indications of technological developments that are bound to transform the economy. It reveals how innovation is driving the rise of additive manufacturing.

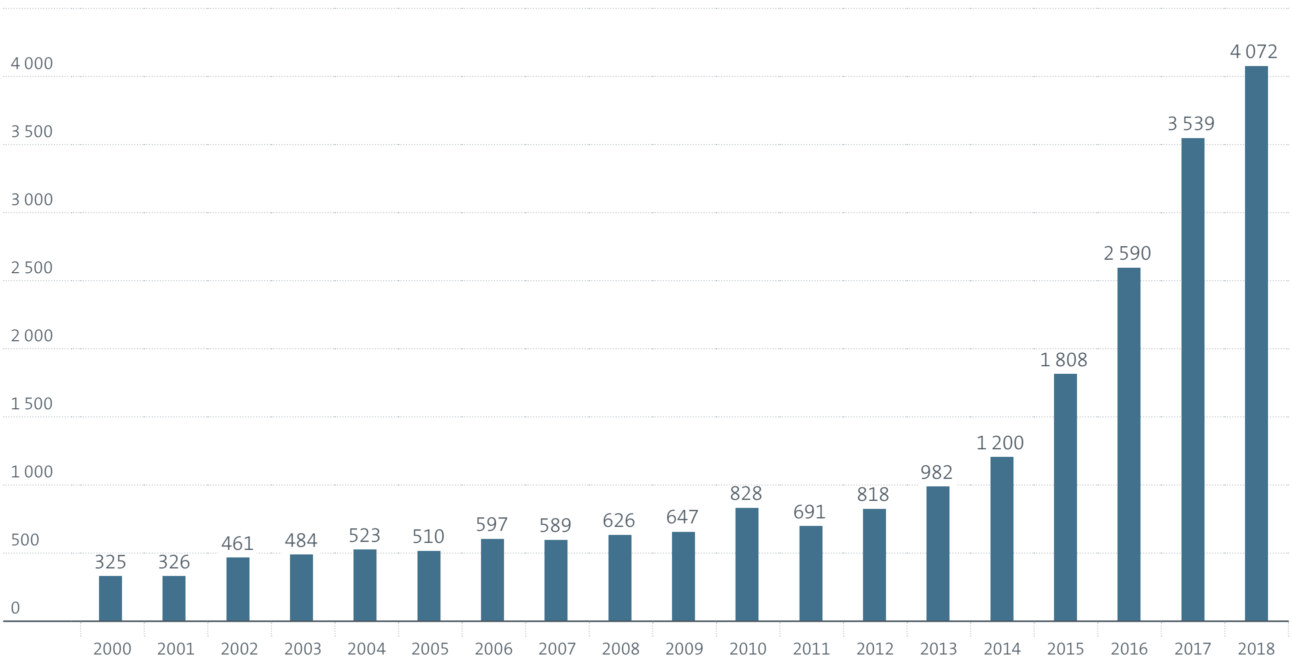
Key findings

AM innovation is taking off

Innovation in AM has accelerated sharply in recent years, with more than 4 000 patent applications for inventions relating to AM filed at the EPO in 2018 alone. During the years 2015 to 2018, AM patent applications grew at an average annual rate of 36%, which is more than ten times faster than the average yearly growth of patent applications at the EPO in the same period (3.5%). New industrial applications of AM technologies account for the largest share of patent applications in AM so far (50%). Other patent applications are related to machines and processes (38%), innovation in materials (26%), and digital technologies (11%). Almost 23% of AM patent applications relate to two or more of these different technology sectors.

Figure 1

Patent applications in AM technologies at the EPO, 2000-2018



Source: European Patent Office

Industrial applications of AM technologies span a large variety of industries. The use of AM in the medical and health sectors has generated the largest number of patent applications since 2010, followed by the energy and transportation sectors. However, rapid growth of AM applications is also observed in areas such as industrial tooling, electronics, construction and consumer goods, and even in the food sector.

Figure 2

AM applications at the EPO by application domain, 2010-2018

	2010	2011	2012	2013	2014	2015	2016	2017	2018
Health	246	223	266	294	393	423	546	720	907
Energy	38	41	59	103	120	288	428	488	436
Transportation	27	24	24	54	57	101	181	215	278
Industrial tooling	58	23	44	40	50	81	124	148	163
Electronics	42	28	25	25	40	71	84	107	137
Construction	26	15	9	18	21	55	58	83	111
Consumer goods	5	7	18	9	18	43	64	86	97
Food	3	7	4	5	10	7	17	29	23

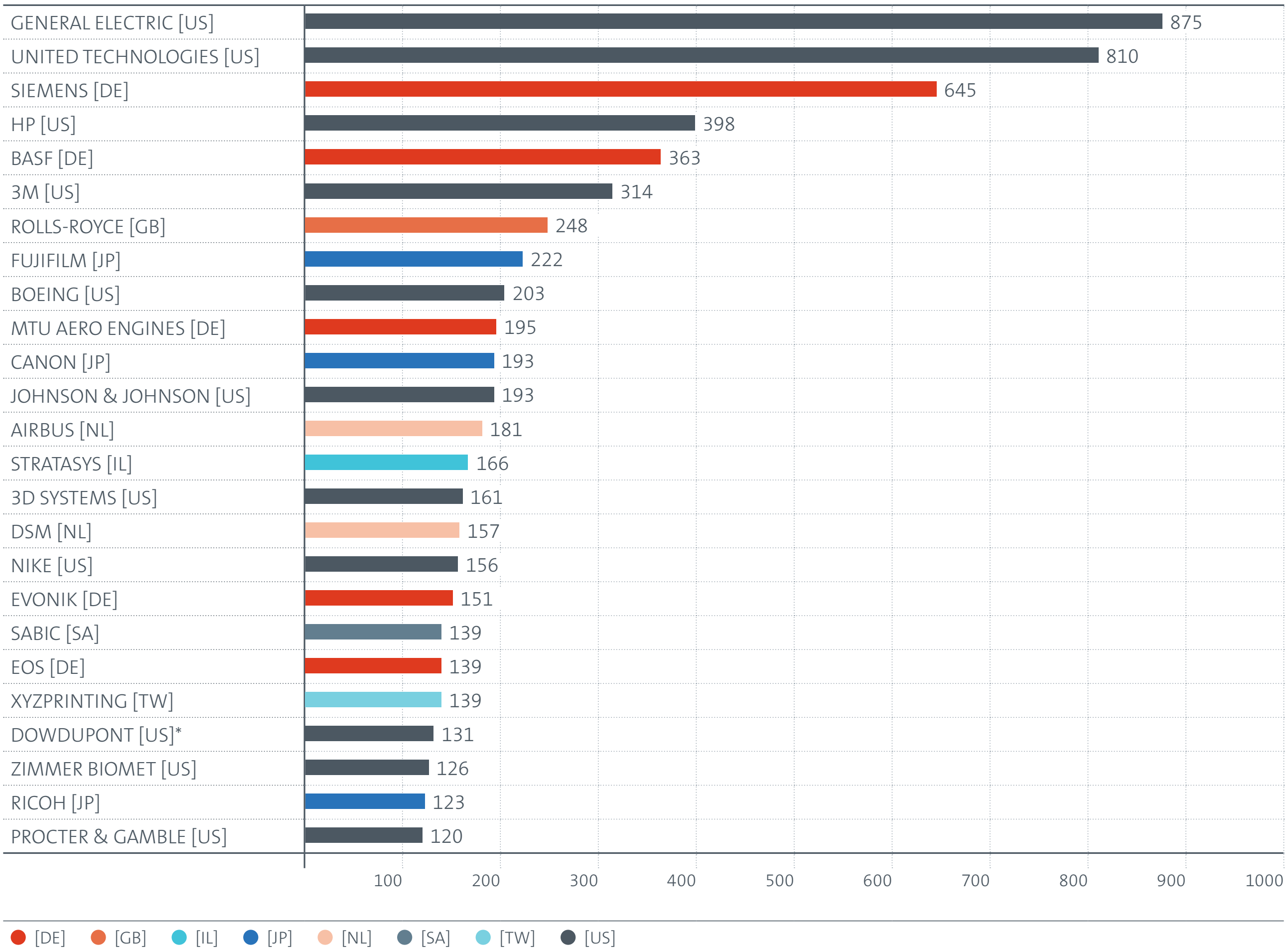
Source: European Patent Office

A highly diverse range of players

Twenty-five companies accounted for about 30% of all AM patent applications filed with the EPO between 2000 and 2018. They include large companies from a range of sectors, including transportation, chemicals and pharmaceuticals, information technology, electronics, imaging and consumer goods, as well as pure 3D-printing specialists such as Stratasys, 3D Systems and EOS. The US and Europe dominate the ranking, with 11 US companies and eight European companies in the top 25 applicants. Of the top European applicants, five are German companies.

Figure 3

Top 25 AM applicants at the EPO, 2000-2018



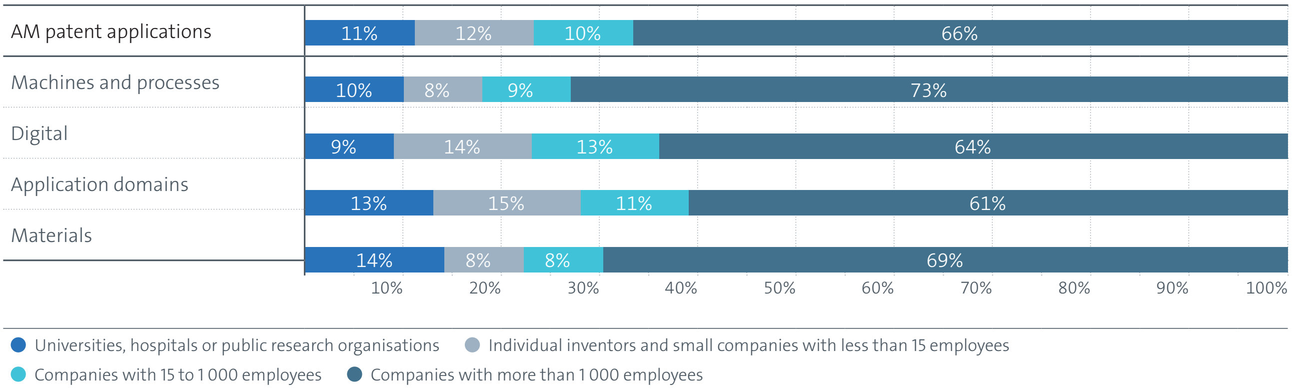
Source: European Patent Office

* DowDuPont was dissolved into three separate companies in 2019. For the purpose of this study the old company name is used.

While two out of three patent applications in AM technologies were filed by very large companies, companies with less than 1 000 employees accounted for 22% of applications. Individual inventors and small businesses with less than 15 employees generated 12% of patent applications in AM. These small companies are especially active in digital technologies and new application domains. Universities, hospitals and public research organisations were responsible for over 11%, mainly concentrated in new materials and application domains for AM.

Figure 4

AM patent applications by applicant type and AM technology sector, 2000-2018



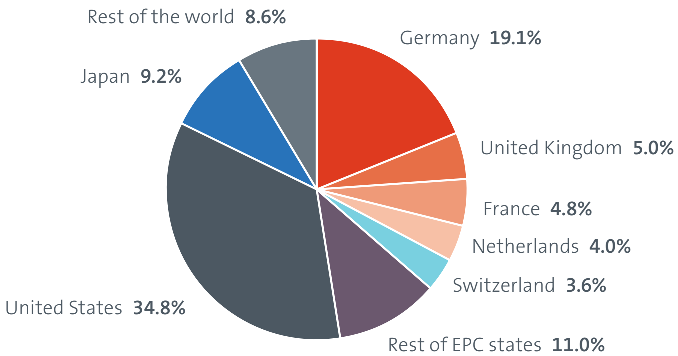
Source: European Patent Office

Europe and US at the forefront

Europe and the US have a strong lead in AM innovation, with 47% (Europe) and 35% (US) of all AM inventions for which a patent application was filed with the EPO since 2010. Europe's leading position is largely due to the performance of Germany, which generated 19% of all patent applications in AM. Outside of Europe, Japan is an important innovation centre for AM technologies (9%), while R. Korea (1%) and P.R. China (<1%) made relatively modest contributions.

Figure 5

Geographic origins of AM applications, 2010-2018

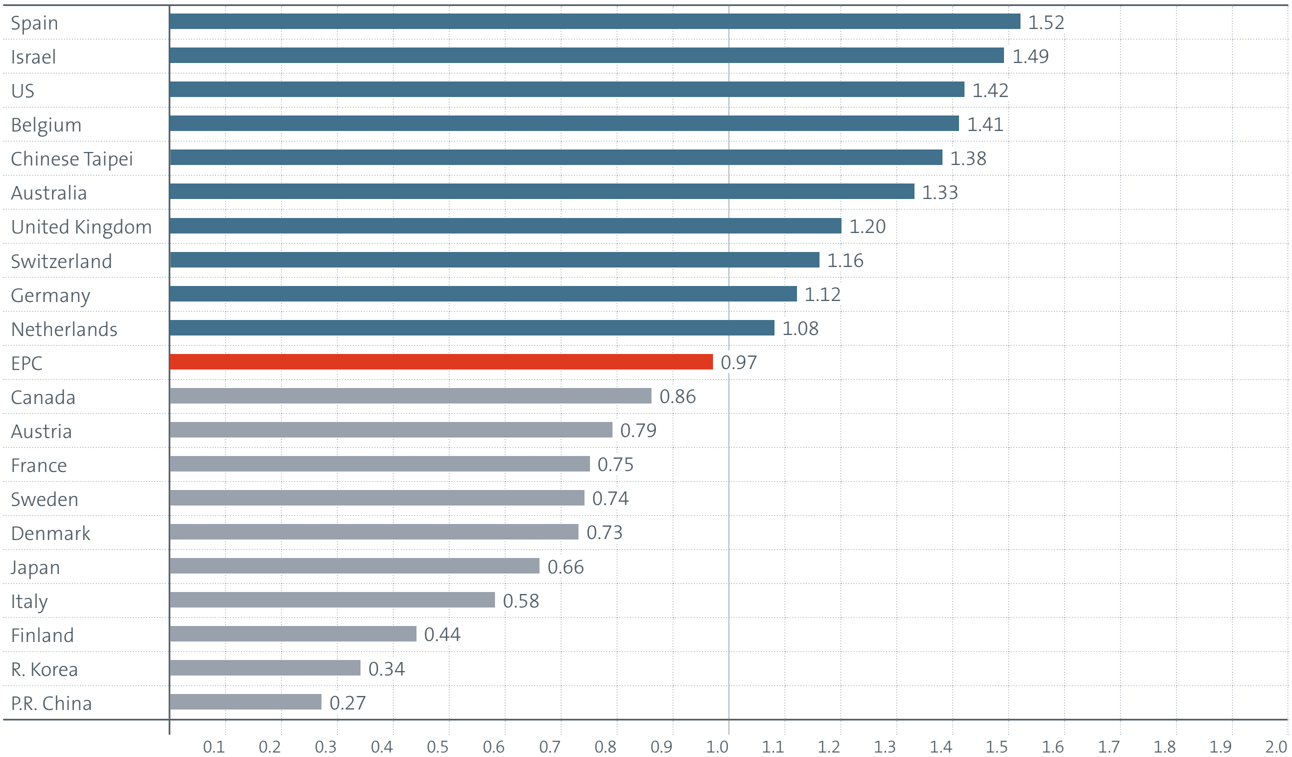


Source: European Patent Office

A revealed technological advantage (RTA) above 1 further indicates a pattern of country specialisation in AM patenting. At the global level, Israel, the United States, Chinese Taipei and Australia show a strong specialisation in AM innovation according to this indicator, whereas there is no such specialisation in the case of the EPC area as a whole. A closer analysis of European countries however reveals a strong pattern of specialisation in AM patenting in some EPC conracting states. This is the case for Spain, Belgium, the United Kingdom, Switzerland, Germany and the Netherlands.

Figure 6

Revealed technological advantage (RTA) in AM technologies of the top 20 countries, 2010-2018



Source: European Patent Office

Note: Only countries with at least 100 patent applications in the period 2010-2018 have been considered.

Introduction

This study by the European Patent Office is intended to inform users of the patent system and the broader public about a technology trend that is set to transform a wide range of industry sectors. Additive manufacturing (AM), more commonly known as 3D printing, is radically changing the way in which products are made, opening up new possibilities in engineering and bringing the means of production out of distant factories into every high street and even into our homes. By providing more resource-efficient, flexible and decentralised production processes, it is paving the way to a safer, smarter and more sustainable world.

What is additive manufacturing?

Manufactured objects, from household items to motor parts, have been produced for centuries using the same conventional processes, such as forging, casting and machining. Conventionally, material is either poured into a mould and shaped by means of dies, presses and hammers, or it is milled or carved from a larger block of material (subtractive manufacturing).

Additive manufacturing offers a radically different approach. It uses a print head, nozzle or other printer technology to deposit thin layers of material one on top of another until a complete three-dimensional object is formed. By changing the dimensions of each layer, objects of fantastic complexity can be created in ways that no other manufacturing process has ever achieved. This approach is compatible with a large variety of materials, from metals and polymers to concretes and live cells, and therefore has a wide range of applications.

AM is also – and most importantly – a digital technology, and as such one of the key drivers of the Fourth Industrial Revolution (EPO, 2017). If a completely new product is being made, a 3D virtual design of it must first be crafted in a computer-aided design (CAD) file. Alternatively, a digital copy of an existing object can be created with the help of a 3D scanner. The availability of a digital 3D model is thus a prerequisite for the AM production of a physical object, and allows for highly sophisticated shapes or geometries. Once created, digital models can be widely and instantly diffused at virtually no cost, enabling the local fabrication of small volumes, or even of single items. Importantly, they can also be modified, allowing in turn for virtually infinite product differentiation and the mass-customisation of 3D printed objects.

An emerging technology with disruptive potential

According to available estimates, sales of 3D printed components have been growing at an average rate of 26.9% over the last 30 years, and the market size of the AM industry passed the USD 10 billion (EUR 8.9 billion) mark in 2019 (Wohlers Associates, 2019). Commonly used materials are widely available, and the quality of some 3D printed parts already matches or even exceeds the quality of parts produced by conventional methods. Today, AM technology is mainly used for prototyping, but is also used for industrial production in aerospace, medical industries, power and energy, and some consumer markets (architecture, footwear and eyewear). In addition, it still has a strong untapped potential in automotive, fashion, textiles, food and printed electronics. As the technology further expands to new materials and applications, it is therefore expected to generate enormous growth opportunities throughout manufacturing industry, which has a market size of EUR 10.7 trillion (USD 12 trillion) (AMFG, 2019).

The rise of AM is also set to have a profound economic impact on supply chains and business models in the years to come. AM streamlines and expedites the product development process, since most parts can be developed and quickly iterated in the digital world. While originally used for prototyping, its value is now seen in making industrial manufacturing more efficient, by using fewer resources while making it easier and cheaper to build complex shapes, geometric features and custom one-off designs (WEF, 2020). As the technology matures, it has the potential to redesign entire industry value chains, with further impact on the price of goods, consumer experiences and labour market conditions. The rise of AM will then oblige companies to rethink their distribution models and to adapt to new forms of competition, while facing the challenge of creating appropriate legal frameworks to safeguard competition.

Aim of the study

The study focuses on the technologies underpinning the rise of AM and provides a window into the latest AM inventions that will shape tomorrow's economy. Aimed at decision-makers in both the private and public sectors, it provides a unique source of intelligence on the high-tech drivers and innovation trends behind AM, based on the latest information available in patent documents and the technical expertise of patent examiners.

AM is driven by technical progress, and therefore by patented inventions. Companies and inventors make use of the temporary exclusivity conferred by patent rights to market their innovations and, in doing so, to recoup their R&D investments. The EPO is responsible for granting patents which can be validated in up to 44 countries in Europe and beyond. As one of the world's main providers of patent information, it is therefore uniquely placed to observe the early emergence of these technologies and to follow their development over time. The analyses presented in the study are a result of this monitoring.

The report provides a comprehensive overview of the scope and dynamics of innovation in AM. It identifies the key technology building blocks of AM and shows how these technologies are being integrated into business applications, offering new opportunities for innovation and value creation in a wide range of industries. The relevant patent applications have been identified and assigned to one or more subsectors of AM technologies, allowing for the creation of comparable, up-to-date patent statistics on trends in AM inventions. The resulting patent statistics indicate technological and market trends up to 2017. Other metrics have been deployed to assess the performance and technology profiles of countries and companies, helping to uncover new industry dynamics.

Outline of the study

Chapter 1 discusses in further detail the current state and expected development of AM in the global industry. Chapter 2 sets out the methodology used in the study to identify and link inventions to the different technology fields underpinning AM. Chapter 3 presents the main trends in patent applications, while Chapter 4 focuses on the top patent applicants involved in AM. Chapter 5 analyses the global origins of AM inventions filed at the EPO, while Chapter 6 looks more closely at European countries. The study also contains three case studies on selected AM technologies.

Patents support innovation, competition and knowledge transfer

Patents are exclusive rights that can only be granted for technologies that are new, inventive and industrially applicable. High-quality patents are assets which can help attract investment, secure licensing deals and provide market exclusivity. Inventors pay annual fees to maintain those patents that are of commercial value to them; the rest lapse, leaving the technical information in them free for everyone to use. A patent can be maintained for a maximum of twenty years.

In exchange for these exclusive rights, all patent applications are published, revealing the technical details of the inventions in them. Patent databases therefore contain a wealth of technical information, much of which cannot be found in any other source, which anyone can use for their own research purposes. The EPO's free Espacenet database contains more than 120 million documents from over 100 countries, and comes with a machine translation tool in 32 languages. Most of the patent documents in Espacenet are not in force, so the inventions are free to use.

1. The rise of additive manufacturing

1. The rise of additive manufacturing

1.1 Short history

AM brings together different technologies, some of which have existed since the 1950s: computer-aided design (CAD), computer-aided manufacturing (CAM), laser and electron energy beam technology, computer numerical control (CNC) machining and laser scanning. Applying these technologies to a variety of materials led to the start of a whole new industry at the end of the 1980s, generating a growing number of patent applications. The commercial use of AM emerged in 1987 with 3D Systems' stereolithography (SLA), a process that solidifies thin layers of ultraviolet (UV) light-sensitive liquid polymer using a laser. The last 30 years have witnessed the growth of AM into a fully fledged industry.

Initially, AM was almost exclusively used for producing prototypes, and it soon became well established in that field. It has since been deployed to make end-products, and this is where the sector reveals its strongest growth potential. AM can provide complex intermediate components and final products that in the past could only be made by hand or by several consecutive work steps. As almost any geometric form can be produced by AM, the technology is now used predominantly for small series of highly complex components. However, the shift from prototyping to end-product manufacturing requires further development in the sectors of hardware, e.g. printers and printing methods design and print software as well as materials used in printing.

These developments will be necessary in order for large-scale production and better quality control to become routine in the reproducibility of the products. While AM adoption is still at an early stage, accounting for less than 1% of total manufacturing value added in 2018, forecasts predict that AM could ultimately come to represent 5% or more of global manufacturing as the technology will further mature (Wohlers Associates, 2019). The AM industry is currently developing at an enormous speed with a market size which passed the USD 10 billion (EUR 8.9 billion) mark in 2019 (Wohlers Associates, 2019). Depending on the underlying assumptions, it is expected to expand with an average growth rate (CAGR) of between 18.2% and 27.2% in the coming years, to exceed EUR 18.5 billion (USD 20 billion) by 2022 at the latest (see Figure 7).

Figure 7

Market size and forecast of AM products and services

Note: Predictions are based on recent market forecasts from Wohlers Associates, SmarTech, MarketsAndMarkets, ReportLinker, ResearchAndMarkets and MarketWatch. An exchange rate between USD and EUR of 1.10 has been applied.

1.2 Economic impact

Beyond prototyping, the current advantages of AM are seen as making industrial manufacturing more efficient by using fewer resources while making it easier and cheaper to build complex shapes, geometric features and custom one-off designs. By making local fabrication in small volumes and close to the end user viable, AM has in particular the potential to disrupt established practices of mass production in distant factories.

AM is already proving its worth in niche applications, especially for customised products or where complexity needs to be mass-produced. But recent developments show promising results even for serial production. The cost of making complex shapes will be reduced while the potential for customisation will increase, thereby allowing for cost-efficient mass customisation. AM likewise makes it easier and cheaper for factories to switch between making different types of products without having to change machines, reset equipment and bring in new materials. Lead times are considerably reduced, allowing for quick changes in product mix and just-in-time manufacturing. Individual parts, hitherto produced in a multitude of steps, can now be produced in a single step. AM can help create strong, light structures that would not be possible using other methods, saving raw materials and adding new functionalities to the products.

Benefits to the environment are multiple: lighter and stronger products, less energy consumed in production, reduced production waste, decreased transportation, packaging and storage due to localised production and shorter supply chains, as well as fewer materials and less inventory needed. Most importantly, AM enables production to take place on demand at the place and time required, with a minimum of waste and pollution. AM will also help promote a "repair culture", making it easier for consumers to print spare parts for household goods and appliances, instead of disposing of them.

Beyond production, AM is expected to have a profound impact on supply chains, leading to a redistribution of where things are made and moving production closer to the end-user or customer. Supply chains will thereby be shortened and made more dynamic, with a shift from make-to-stock towards make-to-order, and low or no inventory anymore. On-demand, single-step manufacturing will shorten and simplify the supply chains, rendering them less vulnerable to disruption.

In this context, AM-based business models will be focused on speed, customisation and decentralisation. AM has the potential to speed up design iteration and production, allowing manufacturing entities to respond quickly to customer demand through customisation and increased innovation. The predicted reduction in retooling costs can render it easier for smaller companies to bring products to the market and compete with capital intensive incumbents. AM will facilitate more distributive, decentralised manufacturing as, in theory, factories can be set up in every city or even neighbourhood and consumers can become micro-manufacturers. AM further has the potential to shift the balance towards a circular economy as the input material is incorporated into the printed output that can be re-fed as input material.

1.3 Intellectual property rights

A further area impacted by AM and one which also needs to adjust and adapt to accommodate the shift in paradigm is intellectual property (IP). In future, the production of a vast array of decorative and functional articles will be in the hands of the broader public. This democratisation of production will not only disrupt supply and distribution patterns, but impact many IP rights too. Designers of new products will be able to license their designs directly to the consumer, who can then print the object locally. Just as new digital platforms for streaming video and music have led to a boom in creativity and new commercial opportunities, so the sharing of 3D design files for printing anywhere in the world is likely to create new business models. At the same time, legislators must ensure that IP regimes adapt to ensure fair protection and remuneration for designers.

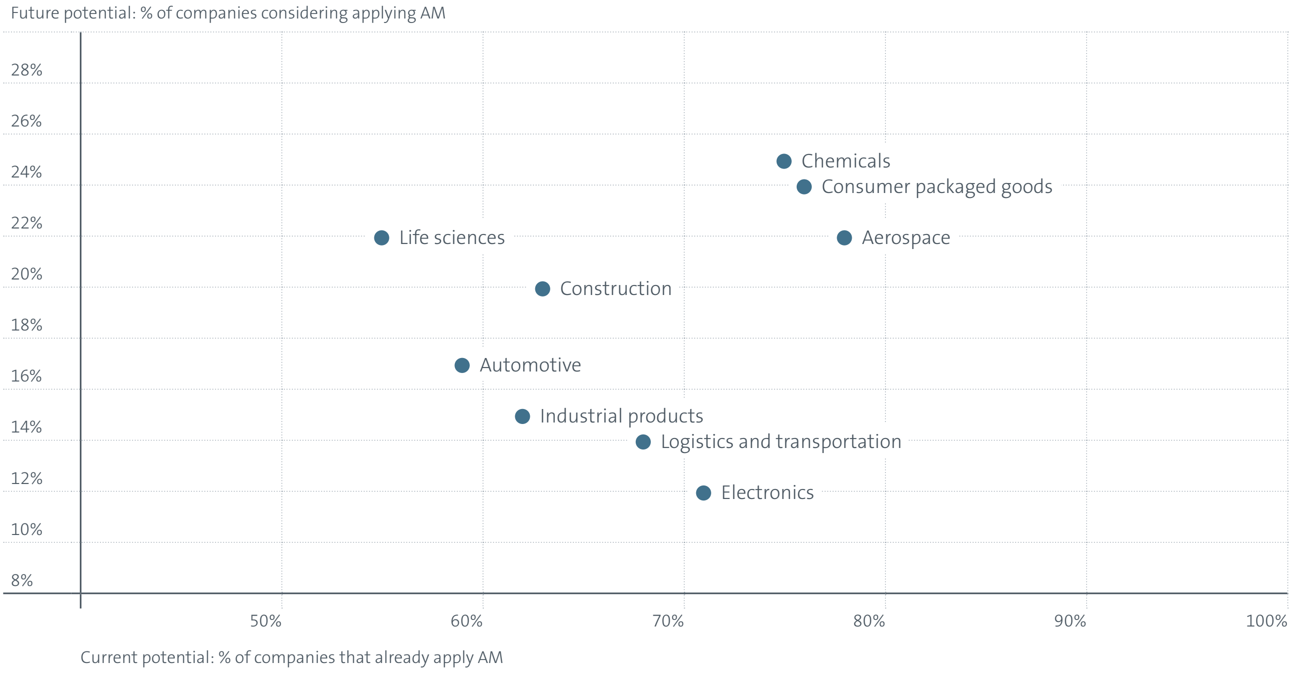
Additive manufacturing provides a fascinating example of how different intellectual property (IP) rights can overlap. Printers execute instructions from digital files that are protected by copyright. The 3D printed objects created thanks to AM may be registered for design protection, although some of them, such as a figurine or vase, are also aesthetic and therefore protected by copyright. Other products such as tools or components with functional features could be eligible for patent protection of novel and inventive technical aspects. But patents mainly protect both the machines that do the additive manufacturing and the processes that these printers carry out. As illustrated by this study, patent applications for the technologies enabling AM have seen a dramatic growth over the last 20 years, involving a wide variety of innovations in machines, materials and processes.

1.4 Adoption of AM: current state and potential

The quality of some 3D printed parts already matches or even exceeds the quality of parts produced by conventional methods. The availability of materials used in AM is increasing rapidly, and most of the commonly used materials are widely available today. In terms of usage, AM is still predominantly used for prototyping (38.6%), followed by the production of finished goods on both small and large scales (28.4%) and the production of tooling (18.5%), as well as for educational and research purposes (9.9%) (Wohlers Associates, 2019). The diffusion of AM technologies has also started to impact numerous technical fields, including healthcare, automotive, aerospace, housing, industrial tools, footwear and food processing. Although familiarity with and exposure of companies to AM technologies is already high in some industries, there still exists a strong potential for further growth (see Figure 8).

Figure 8

Industry experience with AM technology



Source: https://www.ey.com/en_us/advisory/how-3dp-is-moving-from-hype-to-game-changer

Note: Data is based on the EY global 3DP survey of 900 global companies, April 2019.

In terms of traditional materials, polymers and metals are ranking highest in AM technologies, with new materials featuring new properties quickly appearing on the market. The focus in this area is on the commercialisation of materials with finished part qualities, suitable for factory production and consumer goods. Examples of AM applications are provided in Table 1. They include the medical field as well as architecture and construction. In the medical field, the main application is the personalisation of surgery using AM to create anatomic models derived from medical imaging data, as well as the serial manufacturing of implants. In architecture and construction, AM has the potential to reduce energy consumption, with the largest potential in feedstock reduction and its transportation. Commercial implementation and adoption is, however, lagging behind other sectors and end-user parts are predominantly available for high-end interior design.

Table 1

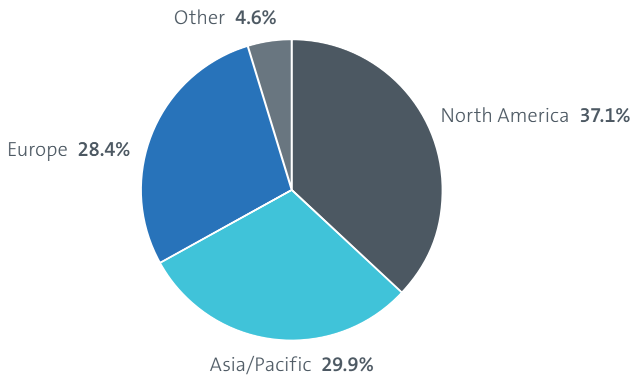
Use cases of AM technology for the production of final parts

Aerospace	– Metal fuel nozzles – Plastic brackets, clips – Integrated hydraulic systems, actuators – Pipe elbows for fuel systems – Titanium family parts – Aluminium parts – (Turbine) blades – Aircraft parts – Ducts – Cable stays – RF filters for communication satellites
Energy	– Rotors, stators, turbine nozzles – Down-hole tool components and models – Fluid/water flow analysis – Flow meter parts – Mud motor models – Pressure gauge pieces – Control-valve components and pump manifolds
Medical/dental	– Titanium-alloy orthopaedic devices (hip implants) – Implants for facial and skull disorders – Copings for crowns and bridges – Complete dentures
Footwear	– Midsoles – Heels – Insoles – Custom footwear
Motor vehicles	– Spare parts – Body shell parts – Chassis joints

The motor vehicle (19.6%), aerospace (17.7%) and industrial and business machines (19.8%) industries contribute the most to revenue in the AM sector (Wohlers Associates, 2019). They were the first to recognise the potential and make use of AM technologies. Consumer products and electronics (13.6%), medical and dental industries (11.5%), academic institutions (4.7%) and government and military (5.2%) also utilise the multiple possibilities offered by AM. Currently, the main industries exploiting AM options are to be found in Europe and the US (Figure 9).

Figure 9

Geographical distribution of the adoption of AM technologies measured by the installation of industrial AM systems



Source: Wohlers Associates, 2019

A growing number of companies also specialise in the development and supply of AM technology systems. A total of 177 such producers existed worldwide in 2019 (Wohlers Associates, 2019), all of which showed high rates of R&D intensity (30% on average, with the biggest manufacturers spending approximately 15%). One of them, 3D Systems, set up in 1986 by Chuck Hull, one of the founding fathers of 3D printing, has become a market leader, reporting EUR 600 million (USD 687.7 million) in revenue in 2018 (www.3DSystems.com). A lively start-up scene is also developing, mostly in the US, but also in Europe.

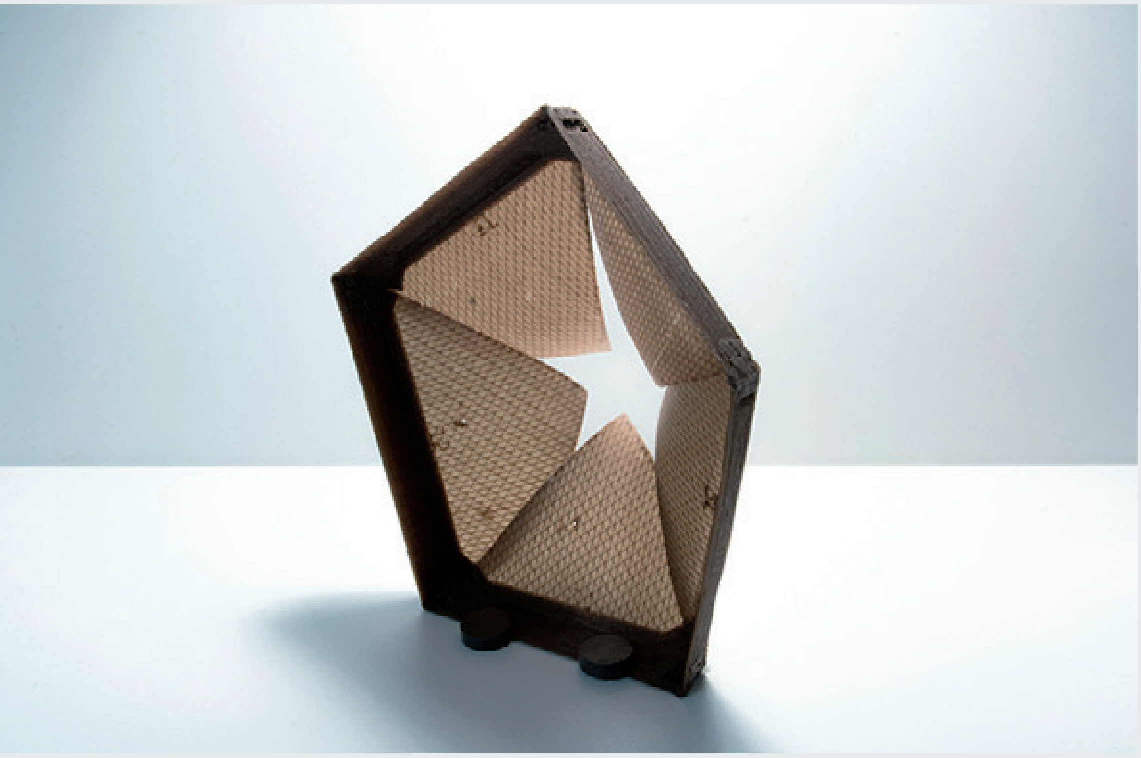
1.5 Innovation challenges

AM still faces a number of challenges that condition its deployment and impact. The cost of the raw materials for printing can be prohibitive at times, while the requirement for post-processing in the form of smoothing and sanding or assembling can still be considerable and costly. By way of example, polymers as raw materials for AM are 20-100 times more expensive than those for traditional, subtractive manufacturing (Wohlers Associates, 2019). Printing machines can currently only print with one material at a time, while electronics or wiring cannot be integrated into 3D printed objects. The printing speed is often too slow, rendering production times too long. Ultimately, the same design printed on different printers could result in different end-products depending on the environmental conditions, the material used, or even the operator, giving rise to reproducibility and quality assurance considerations. Advances in design engineering, software, material science and standardisation/certification (e.g. in the specifications in the design file, such as process parameters and material composition) will reduce these limitations over time.

Observing the industry, the major trends discernible are materials diversification, design progress, mass customisation and collaboration and consolidation. The pace with which new materials are being introduced is increasing, as is the number of materials suppliers. This is driving down costs and improving both the properties as well as the quality of the materials. At the same time, progress is being made in simulation and optimisation tools. ISO standards are being developed for AM design, indicative of a consensus within the industry. Personalisation and mass customisation are becoming cheaper thanks to custom product design. Since no one company alone can offer all the services required (design, simulation, parts building and testing), it is expected that innovation will be driven by a growing number of partnerships and collaborations, followed by consolidation in the market.

At the same time, research is broadening its scope to include a more extensive materials palette, and an explosion in materials suppliers has been observed. A significant area of research is currently in composite and hybrid materials, but developments are underway across all classes of materials, including metals, ceramics, polymers and glasses. Finally, existing materials are being utilised for new AM processes, providing new product options using such materials.

Case study: 4D printing



Four-dimensional (4D) printing is concerned with 3D printed objects that can self-assemble or reshape themselves with time. 4D printed products can change shape, colour or size to suit particular applications after first being made by conventional additive manufacturing (AM).

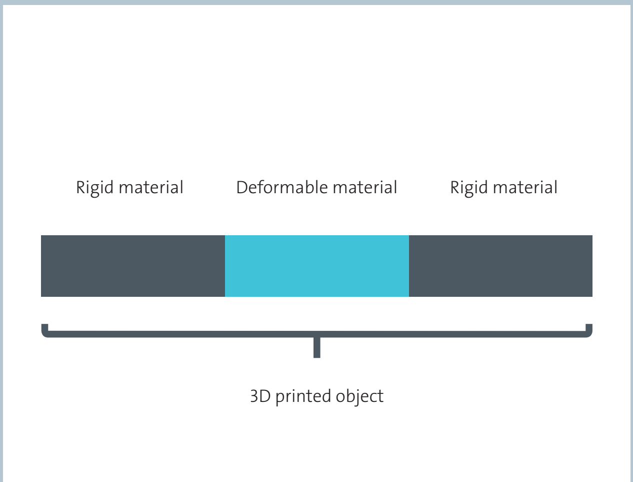
4D printing involves creating objects with special single or multi-material components which change in a controlled way either spontaneously or in response to external stimuli. In many applications the deformation can be reversible; when the external influence is removed, the component reverts to its original form. The significant difference between 3D and 4D printing is the time dependency of the spontaneous or stimulated change in size, shape or colour. As in relativity theory, time is the fourth dimension.

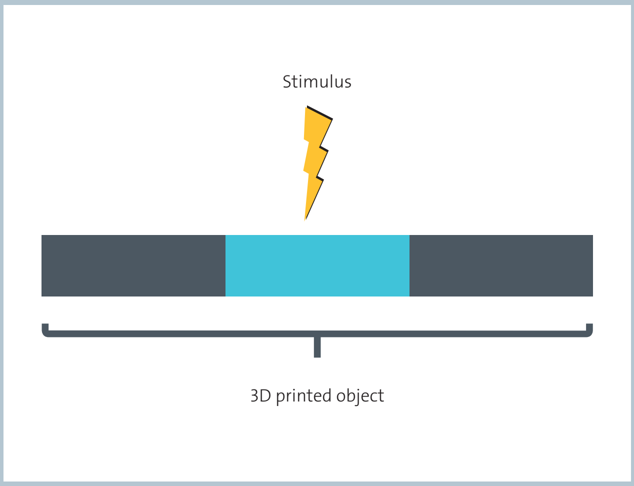
4D printing is currently at proof of concept stage. However, patent filings have increased significantly since 2013, albeit from a very low starting point. The current worldwide market for 4D printing technology is valued at nearly USD 100 million (2020) and is estimated to grow rapidly, reaching nearly USD 540 million by 2025 (Marketsandmarkets, 2016). Based on predictions by leading consultants, the technology is expected to become mainstream in about 10 years.

How it works

Shape-changing 4D printed components are formed from 3D printed objects consisting of deformable materials arranged between rigid materials.

The deformable materials can change shape when exposed to external triggers such as light or heat, or chemicals even as simple as water.





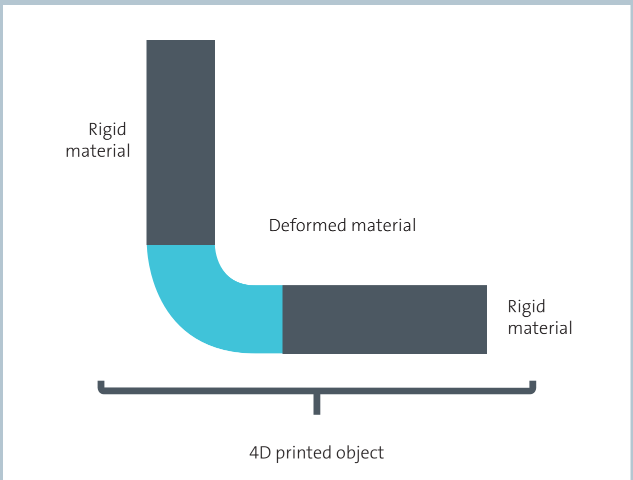
Materials

The essential materials concepts associated with 4D printing are shape-memory materials and smart materials, in other words programmable matter. Inherent strain when built in to the precursor 3D product can be relaxed to allow the component to unfold like a butterfly wing or blossoming flower. To be applicable specifically in 4D printing processes and products, responsive materials must react in a controlled way to external electrical and/or magnetic influences, to light and heat, to pressure or tension, or to selected chemicals. To date, hydrogels and shape memory polymers (SMPs) are the two main active polymers used in 4D printing. Photocured SMPs have been used in 4D printing with both commercial and research printing technologies based on photopolymer inkjetting and projection microstereolithography.

Digital, Machines and processes

The hardware and software for 4D printing is largely similar to that for 3D printing with some limitations arising from materials which are suitable for 4D printing only. Present-day processes may still impose certain geometrical constraints on 3D printed objects, which are the precursors of shape-changed items. For example, low grade fused deposition modeling (FDM) and inkjet printers cannot produce shapes with acute angles of extended portions, such as flanges or brackets, because a new layer must be able to be deposited on a preceding layer. Conversely, SLA and SLS create shapes from a powder bed or resin pool respectively. The powder or resin is able to function as a support for successive layers of material, and so overhanging shapes are possible with these methods. 4D printed objects which move after being printed can be an effective strategy to circumvent the geometrical limitations imposed by current 3D printing hardware.

In this example the deformable materials act like hinges between the rigid materials and, having been triggered, they change the shape of the entire component.



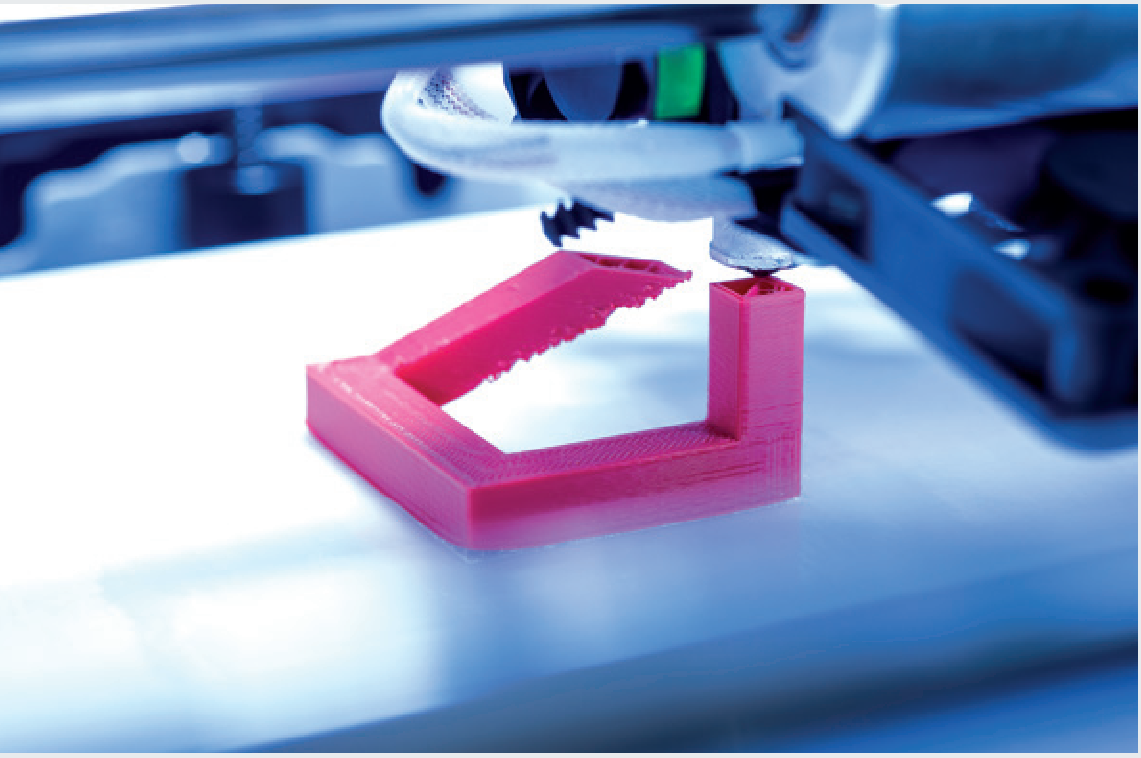
Application domains

4D printed components find application where the environment may be restricted, delicate or sensitive, or where manual intervention is not possible. In medicine and healthcare, 4D printing could be used to create drug capsules that release medicine at the first sign of an infection, using an increase in body temperature as a trigger. Also, 4D printing technology could have medical applications such as stents that expand after being exposed to heat. In aerospace, components and structures made by the technology could change shape in response to different environmental changes in temperature, air pressure or other factors. They could replace hinges, or even motors and hydraulic actuators, making planes simpler and lighter in weight. Other possible areas of application can be found in robotics, furnishings, self-assembly, hazardous environments and wearable goods.

Challenges

Developing appropriate materials for 4D printed objects currently poses a big challenge. Hydrogels are soft, and as a result the stiffness of the final structure is relatively low. This can be overcome by combining the soft gel with a stiff SMP. The swelling mechanism is based on solvent diffusion and the reaction time is relatively slow, especially for large structures. The resultant structure is also not permanent, such that loss of solvent can result in the structure reverting to its original, or some other, geometry. 4D printing with SMPs is generally a complex procedure involving synthesis/processing by 3D printing and thermomechanical programming (including sequential heating, mechanical loading, cooling and removal of load, and deployment/actuation). Thermomechanical programming often requires special jigs and fixtures to apply mechanical loads and a well-controlled thermal environment. However, innovation in these areas is speeding up, such that these problems will likely be overcome in the very near future.

Case study: Bioprinting



3D printing for medical purposes such as the manufacture of custom implants and prosthetics usually involved plastics, metals and ceramics materials. The field of cell-based bioprinting did not emerge until 2003, when Thomas Boland used a modified inkjet printer to print cells. Subsequent developments led to it being used to create more complex tissues and organs.

According to recent market research, the global market for 3D bioprinters and biomaterials amounted to USD 651 million in 2019,[1] and is expected to grow rapidly over the next few years, with annual growth rates exceeding 20%. By 2024 it is expected to pass the USD 1.5 billion mark, with applications in the pharmaceutical and cosmetology industries.

Biomaterials

The generic term “biomaterials” is used for a class of materials which have one thing in common: they are designed to interact with a patient’s biological system. They have the ability to generate an appropriate response of the patient’s biological system in order not to harm the body. This ability is known as “biocompatibility”. Biomaterials cover a wide range of biocompatible materials, including metals, polymers and ceramics, which are non-living materials. However, there is also a group of biomaterials comprising living materials such as cells or tissue.

The use of cells in combination with additive manufacturing techniques offers the chance to fabricate biomedical parts that maximally imitate natural tissue characteristics. This “3D bioprinting” uses bio-inks, which comprise cells and other cell-supporting materials, to create tissue-like structures for use in medical and tissue engineering fields.

1 See for example https://www.businesswire.com/news/home/20191009005386/en/Global-3D-Bioprinting-Market-Outlook-2019-2024.

State of the art

With additive manufacturing, constructs with the required shape, size, porosity and mechanical properties can be made from a variety of materials. However, when printing said constructs together with cells, certain temperatures, solvents and other cytotoxic materials and conditions such as shear stress, viscosity and humidity, which can adversely affect living cells, need to be avoided or controlled. This limits the choice of AM printing techniques that can be used and requires solutions to allow for a more diverse and precise 3D bioprinting process. The use of cytotoxic photoinitiators, which are hazardous for cells, as well as UV light needs to be avoided in order not to introduce DNA damage to the cells (Kačarević ŽP et al., 2018). Also, laser-assisted methods can be problematic, due to the heat generated by the laser (Karzyński et al., 2018). Moreover, in order for the cells to remain viable, as well as maintain the desired phenotype, the construct needs to allow for the required biochemical and mechanical interaction with the cells, as well as for the availability of a blood supply to provide oxygen and nutrients across the whole construct.

Natural organs and tissues have very unique structures and mechanical properties. To allow for cell interactions and the required mechanical properties the use of different cell types, signalling molecules and patterns is needed. Despite challenges, the use of 3D bioprinting makes it possible to make such products with gradients and details on a scale not possible before. In other words, it enables the formation of concentration gradients of cells and the formation of patterns of signalling molecules, as well as the inclusion of microchannels which enable vascularisation of the constructs or which allow oxygen and nutrient availability across the construct. It also allows for the combination of weak extracellular matrix based hydrogels, or peptides derived therefrom, needed for cellular attachment and survival, with stronger synthetic materials to give the construct the required mechanical properties (Murphy et al., 2019).

Along with *in vitro* (i.e. outside the body) bioprinting, *in vivo* bioprinting, i.e. bioprinting directly onto the body, is also being developed. An example of this is *in vivo* skin bioprinting for burn injuries. The advantage of this technique is that it avoids the need for *in vitro* maturation of the vulnerable printed tissue before implantation (Varkey et al., 2019).

Innovation challenges

Although all these advantages of 3D bioprinting of cell-seeded tissues or organs are promising, and have already been successfully implemented on a small scale, further developments need to be made in the additive manufacturing processes, as well as in controlling the stimulation and differentiation of cells after formation of the structure, to allow for the formation of 3D printed tissues or organs of a clinically relevant size. The formation of a sufficiently large and branched vascular network for delivering the required oxygen and nutrients to the cells remains particularly challenging. Also, improving the resolution and accuracy of printers to allow for more detailed structures and controlled single cell deposition to closely mimic human organs would be useful. As each printing technique has its own disadvantages as well as advantages, combining different printing techniques in future may help overcome some of these limitations. Furthermore, additive manufactured objects today are static. Biomedical devices often need to have dynamic properties, i.e. changes in shape, functionality and property. Therefore further new developments are needed.

When these challenges have been overcome, 3D bioprinting will be a promising tool for making personalised tissues and organs. As in many cases a patient’s own cells can be used, the problems of finding a compatible donor for a tissue, as well as the lack of donors, can be overcome (Xianbin Du 2018). With the generation of bioprinted tissues it may also become possible to replace animal testing for the study of disease and drug screening.

Another important development is 4D printing, a technology which describes additive manufacturing technologies adding another dimension to the device. More specifically, devices can be produced which can alter their shape, function and properties. For this, “smart materials”, e.g. shape memory materials, are used in adapted additive manufacturing processes. The final products can be used e.g. as implants which can grow with the patient or which can change their shape to provoke movement. Moreover, using such a technology in combination with 3D bioprinting of cellular material will open up a whole new range of possibilities in biomedical applications. The cells will proliferate, differentiate, reorganise and create a new tissue matrix, whereas the originally printed scaffold itself may or may not break down over time. A completely new type of personalised product will be formed. Extensive studies will be needed to be able to predict the outcome of such complex 4D printed structures.

Beyond innovation

In addition to technological hurdles, the additive manufacturing of biomaterials faces other, less technical considerations. Questions arise with regard to regulatory and legal aspects, as well as standards, aspects of data protection, intellectual property and ethics. Due to its relatively novel nature, many of these questions have not yet been fully answered.

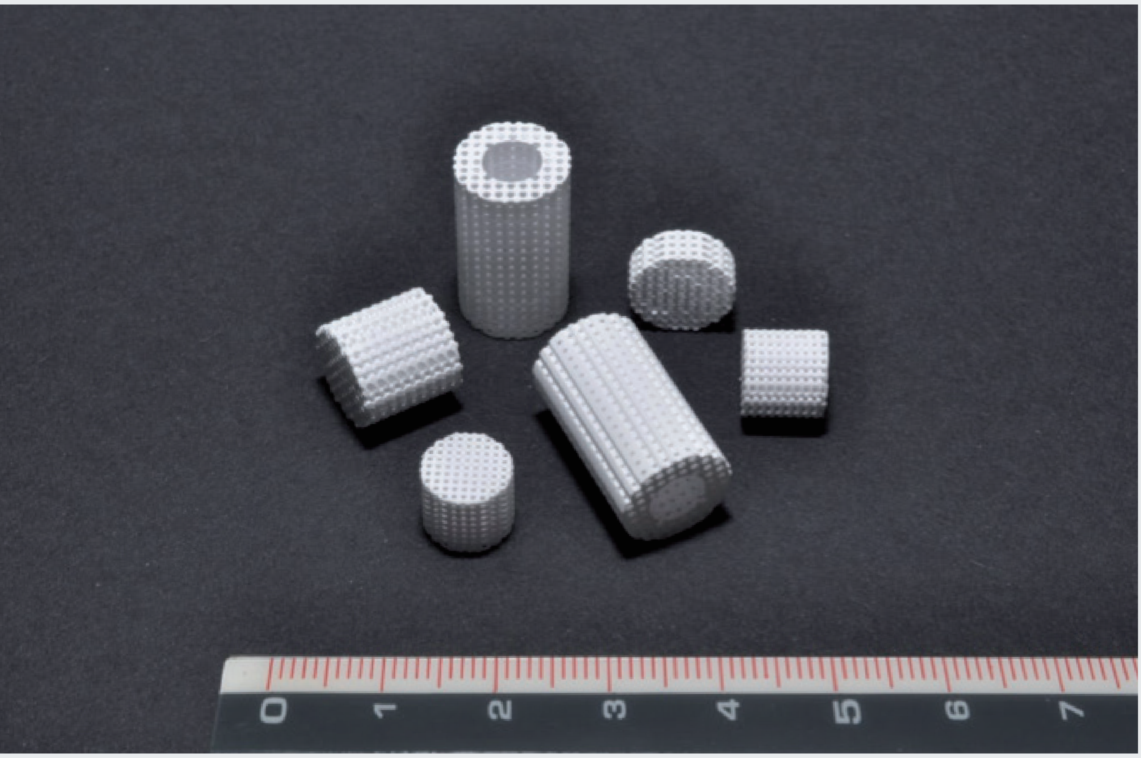
As mentioned before, AM techniques can be used in the medical field with "conventional" materials such as metals, polymers, ceramics or composites and with novel, hybrid materials consisting of cells and, for example, polymers. Medical device regulations and standards cover devices manufactured by "traditional" manufacturing techniques. There is, however, a lack of specific guidance in existing regulations and standards, especially when hybrid materials are used.

In Europe, existing regulations do not give explicit guidance for 3D printed medical devices, while the unclear classification of hybrid materials made from living cells and non-living matrix material by 3D bioprinting creates an additional uncertainty (Kritikos, 2018). In the US, an initial FDA guidance for 3D printed medical devices was issued in 2017, but it did not explicitly include bioprinting (Mason et al., 2019). New ISO standards for process chain certification, hardware and software and feedstock and material properties are in development, although final legislation and standards have still to be defined.

For the manufacturing of personalised medical devices, patients' personal data must be collected and shared between physicians, designers and manufacturers. Furthermore, due to the nature of this new, personalised medicine, 3D bioprinted personalised test devices/organs contain patient specific data as well, so data protection regulations are an important factor in using such medicine. In addition, the ownership of personalised designs, devices and materials is often not clearly regulated (Kritikos, 2018).

Finally, social-ethical questions arise regarding the use of cell source for 3D bioprinting, the affordability of bioprinted organs and the boundaries between therapy and human enhancement. However, the technology offers the possibility of avoiding animal testing and optimising medical treatments, which can be tested in advance on patient cells before use (Vermeulen et al., 2017).

Case study: Ceramics



Due to their various excellent properties, ceramics have always been an important material for many industries. While traditional ceramics, such as clay, have been used for thousands of years, predominantly in construction as bricks and tiles, advanced or high-performance ceramics, such as oxides, carbides, borides, nitrides and silicides, are nowadays used for an increasing range of high-tech parts in aerospace, electronics and the automotive and medical industries. Advanced ceramics, of which the oxides alumina (Al2O3) and (stabilised) zirconia (ZrO2) are currently the most commonly used, exhibit high mechanical strength and hardness, great thermal and chemical stability, good electrical and magnetic performance, and excellent biocompatibility. This makes them the ideal material for diverse applications such as bearings and semiconductors, as well as the restoration of veneers and crowns, and for prosthetic limbs and bone replacements.

The use of 3D printing techniques in the manufacturing process of ceramics was first reported in the 1990s (Chen et al., 2019). Although 3D printed ceramic parts still need to undergo the same secondary process as when produced with traditional methods – post-processing is still needed even for 3D printed parts before they can achieve their desired mechanical and chemical properties and final-part density – additive manufacturing promises to circumvent certain significant limitations of the conventional techniques. First and foremost, additive manufacturing allows the creation of structures with geometries which have not been possible before. Second, since no moulds are required, it is possible to get first prototypes very quickly. Third, small-scale series can be produced more cost-effectively, so mass customisation to better meet individual customer needs can be applied to ceramic parts.

Despite its obvious advantages, the 3D printing of ceramics is, compared with polymers or metals, still at an early stage in its development, with a market size of less than EUR 200 million in 2019 (Smartech Publishing). Challenges in the printing process that may lead to deficiencies in the ceramic parts and the relatively high material costs still pose major obstacles to widespread adoption (AMFG, 2019).

However, research and development activity to improve the mechanical and performance properties of 3D printed ceramic parts is increasing rapidly and continued adoption is driving the cost of materials down. According to recent forecasts and in view of the current speed of technological advancements, it is expected that the 3D printing ceramics industry will reach maturity in 2025, achieving a market size of EUR 3.3 billion (USD 3.6 billion), with opportunities in the aerospace, automotive, marine, energy, electronics, medical and biomedical segments.

Processing of high-performance ceramics

In accordance with the ISO/ASTM standard on terminology in AM, various technologies are now available to process advanced ceramic materials, with different machines and compatible materials (Wang et al, 2019). These methods can typically be divided into direct and indirect processes. Indirect processes include stereolithography, binder jetting, material jetting, extrusion and lamination moulding. In all of these processes, the ceramic material is combined with a resin or polymer to form a green body, which needs subsequent debinding and sintering. Stereolithography has been developed for ceramic materials by Lithoz (see below), by adding ceramic particles to a UV-photosensitive resin. Commercially available material extrusion processes are typically based on either a viscous paste being extruded or the fusion of the accompanying polymer in the nozzle head.

The direct processes such as powder bed fusion or sintering and direct energy deposition (DED) all result in a final product. Unlike polymer and metal powder processing, ceramic powder bed technology covers four different alternatives, depending on temperature and/or the addition of lower-melting substances. These are solid state sintering, chemically induced binding, liquid phase sintering and full melting. Apart from DED, all the processes use relatively small powder sizes, i.e. submicrometers up to a few micrometers. Besides DED, material jetting and some of the extrusion technologies allow for multi-material deposition.

Lithoz, a European success story

The company landscape of ceramics 3D printing technology providers is still relatively small, but is developing dynamically, such that more and more real, practical and commercial applications are beginning to emerge. One example is Lithoz [2], a relatively young, fast-growing Austrian company that developed the patented lithography-based ceramic manufacturing (LCM) process – based on a photopolymerisation process – and provides materials, 3D printers and dedicated software for high-performance, bioresorbable ceramics.

During the LCM process a photosensitive resin filled with a homogeneously dispersed ceramic powder is polymerised. An LED-based projection system, which keeps energy costs at low level, emits light onto the resin and selectively cures the resin and builds up the ceramic part layer by layer. This green part, a composite of ceramic particles within a photopolymer matrix acting to bind together the ceramic particles, must then go through the post-processing steps of debinding, i.e. removing the photopolymer matrix, and sintering. The material density that is achieved with LCM is well above 99% of the theoretically possible density and meets the standards of the ceramics industry. Applications can be found predominantly in the medical and aerospace sectors. Examples range from ceramic cores for turbine engine components to blood pumps and bone implants.

Founded as a spin-off from the Vienna University of Technology in 2011, Lithoz has grown into a flourishing business with more than 70 employees and a subsidiary in the US. The success of the company is rooted in a far-sighted IP strategy that was framed by the transfer support service of the University together with the two founders Johannes Homa and Johannes Benedikt ("Lithoz" in EPO SME Case Studies 2017). The technology was initially developed and the core intellectual property (IP) generated back in 2006, when the two men were researchers at the University. Although the R&D activities and development of the IP were supported by an external partner from the private sector whose core business is in dental applications, the University's technology transfer specialists obtained the freedom to pursue business opportunities for all other applications. This agreement allowed Lithoz to secure exclusive exploitation rights for their technology for non-dental applications and spin off from the university. Being a small start-up, access to a large patent portfolio including European countries, the US, Japan and China, was essential to avoid being blocked by other companies and to ensure a competitive advantage for its high-quality products and services. Today Lithoz has successfully added a strong patent portfolio of its own that helps to secure and strengthen its market position. This is greatly appreciated by its customers and business partners.

2 For the full case study about Lithoz, see epo.org/sme

2. Cartography of AM technologies

2. Cartography of AM technologies

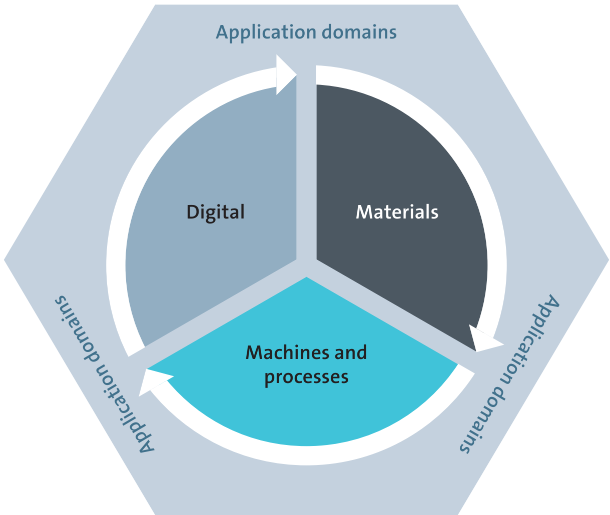
Additive manufacturing (AM) is both an interdisciplinary and a multidisciplinary technology. As a digitised manufacturing process it starts with the digital design representation of a product to be made. It requires the handling of a **digital** file and the instruction of a **machine** to operate in such a way that a product is given shape according to the design, using a **material** with a structure and properties that are fit for the intended **application domain**. Therefore, for the purposes of the cartography of AM technologies, all relevant technologies that support any of these aspects have been taken into consideration.[3]

The AM cartography has been built up on four technology sectors: *Materials*, *Machines and processes*, and *Digital*, which can be employed in different *Application domains* depending on the industry where it is used (Figure 10). *Materials* includes both core materials and "assisting" materials. In the AM technique binder jetting, for example, the "core" material is the powder in the bed, such as metal or ceramic, and the binder is the assisting material. *Machines and processes* refers largely to printers, but also to other peripheral devices that have been developed for the different AM techniques.

The "digital" aspects refer not only to the digitalised design of the product to be manufactured, but also to the control of the printing machine and the process to arrive at a sufficiently high-quality product. In other words, they also cover the monitoring and control of the printing process and the printing machine. *Application domains* is a transversal category covering the applications of AM technologies in different industries. It denotes the main field of use of the manufactured product.

Figure 10

Illustration of the four AM technology sectors



Source: European Patent Office

3 Screen printing (seriography) has not been considered as part of additive manufacturing. Although the technique is explored for micro 3D printing in some areas, it has mainly been applied for 2D printing. The field of 2D printers has been excluded as well, as its inclusion would lead to too many false positive hits.

Each of these four AM technology sectors is further subdivided as follows:

2.1 Materials

Materials are the input for the AM process and are often produced as solids, in powder form, in wire feedstock, or as a liquid. For example, in stereolithography, a bath of liquid photo-sensitive polymers is used for the core material, whereas in binder jetting the liquid binder functions as an assisting material that is added locally to the powder bed.

Five different types of *Materials* technologies have been identified: polymers, metals, ceramics, biomaterials and cements.[4]

– *Polymers*[5] comprise both the synthesis and the modification of compositions. In addition, the production and modification of artificial fibres or textiles was also included. Photo-sensitive materials were also considered.

– *Metals and alloys*[6] cover pure metals, alloy compositions of metals, and combinations of metals and non-metals, such as e.g. in cermets or metal matrix composites. Single crystals were also included.

– *Ceramics*[7] comprise oxides, non-oxides as well as the ceramic-based composites. Glass compositions were also included.

– *Biomaterials*[8] include only materials for the soft tissues and scaffolding, i.e. cell cultures, polypeptides and polysaccharides.

– Compositions of *cements*[9], mortars or artificial stone are the basis for the fifth subcategory.

4 For all of these types of materials, the compositional aspects of patented inventions have been evaluated for the selection. For example, if the invented product was made of a metal alloy, then it was only considered as relevant for the material “metal alloy” if the composition itself was an integral part of the invention, i.e. is reflected in its patent classification. In contrast, if an inventive medical implant uses a trivial metal alloy, the material will not be reflected in the patent classification, so it will not be considered for that material group of the cartography.

5 The selection of polymers for AM purposes is determined mainly by the type of AM technology. For material extrusion methods, a range of thermoplastic polymers can be used. These are melted before application and harden on cooling. Resins based on PLA, PC and styrenics are most commonly used in this field. Acrylates, epoxy resins and polyurethanes, on the other hand, are the preferred resins for photopolymerisation techniques and binder jetting. In powder bed fusion technology, polyamide resins are usually applied (e.g. PA6, PA11, PA12), as well as other polymer materials such as PEEK or TPU. These polymers are usually specially developed for use in AM. They are also the subject of much research, since the end products currently suffer from drawbacks compared with those produced using traditional manufacturing methods – especially when it comes to dimensional stability, mechanical properties, porosity, speed requirements and resolution.

6 Different types of metallic powder have been developed for additive manufacturing: steels, particularly stainless steels and tool steels; aluminium alloys for aerospace applications; nickel and cobalt based alloys for turbine parts; titanium alloys for implants; copper alloys for heatsinks and heat exchangers; and noble metal alloys for jewellery. Material optimisation focuses on two distinct aspects: (a) the fine-tuning of alloy compositions to improve interaction between the powder alloy and the energy beam, and (b) powder rheology optimisation – in particular powder morphology, particle size, size distribution and flowability – to simplify and speed up the deposition of even powder layers and adjust the density of the final product. Furthermore, additively manufactured parts do not require a final sintering step when produced using powder bed fusion and direct energy deposition, for example. Therefore, they have a different microstructure from parts produced by conventional techniques such as casting, forging or injection moulding. This means that specific heat treatments are currently under development in order to tailor the properties of the final AM parts to specific product requirements.

7 In the field of ceramics, selective laser sintering (SLS) is the most common technique for creating a 3D form. The most common ceramic material in additive manufacturing is zirconia (ZrO2), which is used for making teeth, crowns and other tailor-made dental objects. Alternatively, alumina (Al2O3) can be used for these purposes. Ceramic bone-like materials are generally made of phosphate- or silica-based materials. Silicon carbide (SiC) is the most commonly used non-oxide ceramic material in AM. It mainly features in high-temperature turbine components exposed to high temperatures.

8 The field of biomaterials centres on the chemical aspects of implants. The materials and products involved must have certain mechanical, degradation or stability properties as well as a desired shape or ability to be processed. They must also interact appropriately with proteins, cells and tissues, and often be conducive to releasing drugs too. Biocompatible compositions used for the additive manufacture of tissues are called “bio-inks” and comprise materials that mimic natural cellular matrix components. These form three-dimensional porous or hydrogel structures that support or stimulate tissue regrowth. In hydrogel materials, the cells intended to form the new tissue are also often part of the bio-ink. Additive manufacturing allows these gels to be printed in complex shapes. In porous materials, the cells are seeded after the structure is formed or the cells grow into the structure after implantation. One of the 3D printing techniques used here is stereolithography, which uses bio-inks based on known biocompatible polymers that are functionalised to allow photo-crosslinking. These bio-inks can form structures with a high porosity and interconnectivity that are appropriately shaped to fill the tissue defect. It is even possible to provide structures with a printed capillary network to ensure that the cells in such scaffolds have enough nutrients and oxygen to grow into a new tissue. The chemical aspects of bandages, dressings or absorbent pads, materials for surgical articles and for prostheses as well as their coatings have been considered in *Health*.

9 With binder jetting technology a layer of reactive material such as Portland cement can be deposited over a layer of sand. Portland cement or calcium aluminate cement can be used as the powder bed with an aqueous solution of lithium carbonate as the binder. Alternatively, 3D printed powder structures in a geopolymer system have been developed, wherein the powder bed consists of ground blast furnace slag, sand and ground anhydrous sodium silicate (an alkali activator). The 3D printing of wet concrete poses several challenges. These include regulating the pumpability and properties of the fresh concrete in order to have sufficient workability and open time for extrusion, as well as developing its structural properties and strength in particular. Such properties are of major importance when it comes to the complexity and size of the objects printed.

2.2 Digital

A whole range of aspects that are related to digitised manufacturing is considered for the AM technology sector *Digital*. Any process of additive manufacturing starts from a digital representation of a product. This can be done by designing "from scratch" using design software, resulting in a computer-aided design (CAD) file. Alternatively, an existing product or model can be scanned and digitally represented. The digital design is then transformed into a build volume, sliced into layers. To each of these layers printing instructions need to be assigned. These instructions address the distribution of the material, the movement, intensity and form of the energy beam, additional heating or cooling means (optionally), gas (flow) protection, recycling of material, etc. While the object is being manufactured the printing process can be monitored and controlled. The process control is particularly important for high-end products for which certification is a requirement.

Another aspect of the digital character of AM is the possibility to manufacture remote from the place of design. The data files, whether for the design or the manufacturing instructions, therefore need cyber protection. Furthermore, different digital services around the AM process may exist, such as offering various designs on digital platforms to a larger public or facilitating delocalised manufacturing, where parts can be printed by contract, so they are therefore also considered in this part of the AM cartography.

2.3 Machines and processes

Machines and processes in general cover all AM techniques described in the ISO/ASTM52900:2015 standard, namely binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photo polymerisation. Each AM process can differ in the following aspects: type of material it can use, whether the material is consolidated directly in one step or involves a pre-step, where the material is first bonded temporarily, or the form in which the material is introduced and deposited. More detailed aspects related to integral components such as laser optics, electron beam design and extruder heads have been considered as well. Current areas of research cover increasing printing speed and improving the quality of end-products, as well as the possibility to print composite materials.

2.4 Application domains

With the development of AM from a mere prototyping tool to a technology which is capable of creating industrial and health care products in larger series, the fields in which it is an alternative or even superior production method are constantly expanding. To reflect this diversity, eight different application domains have been identified: *Transportation, Industrial tooling, Health, Food, Energy, Electronics, Consumer goods* and *Construction*. Some of these application domains are only just starting to explore the possibilities, whereas others (e.g. hearing aids) have already adapted completely.

Most of these application domains are themselves aggregates of various related subgroups. For example, *Transportation* includes applications in automotive, marine, aerospace and bikes. The *Health* industry was one of the early adopters of AM technologies, because they put customised products for patients within reach. 3D printing techniques are now being used to make not only implants and externally applied prostheses – ranging from cardiovascular implants to hearing aids and dental implants – but also surgery tools, pharmacological preparations and educational models. The *Energy* domain covers heat exchangers, turbine engines, batteries and magnets. With micro-additive manufacturing techniques, allowing high-resolution features, the manufacturing of microprocessors and other electronics is developing, but also aspects related to the embedding of semiconductors within additively manufactured products. *Consumer goods* are focused on furniture, footwear and jewellery, while *Construction* includes housing, piping, tunnels, bridges, and so on. AM is also enhancing more classical manufacturing processes, such as casting and injection moulding, by making a more versatile mould design and manufacturing process possible. These applications are covered in the application domain *Industrial tooling*.

2.5 Linking AM technology to patent data

The identification of patent applications related to the various parts of the AM cartography was carried out using the EPO's in-house expert knowledge, together with scientific publications and studies published by various consultants specialising in AM. This in-house knowledge has been built up over many years of working within the core AM technology fields and collected through a network of AM technology specialists across the EPO. For details of the methodology used to identify relevant patent applications and link them to the cartography fields, see Annex A.

The patent analysis in this report is based on patent applications filed with the EPO (applications filed direct with the EPO or international (PCT) applications that entered into the European phase) in the period 2000-2018. Patent applications filed with other patent offices have not been included, so the statistics do not fully reflect applicants' or countries' overall innovation capacity. However, a strict focus on patent applications at the EPO has several important advantages. First, it makes it possible to report on the most recent patent statistics for the European market, including unpublished patent documents filed in 2018 and only available in the EPO's internal databases. Second, it creates a homogeneous population of patent applications which can be directly compared with one another, as these applications have been filed with the same patent office, seek protection in the same geographical market (Europe) and have all been classified by EPO patent examiners. This approach avoids the national biases that usually arise when comparing patent applications across different national patent offices. A third advantage of focusing on EPO patent applications is that, in most cases, each individual patent application can be considered as representing one technical invention.

However, care needs to be taken when comparing patent applications originating from within Europe with those from elsewhere. While European applicants are targeting their home market when they file a patent application with the EPO, non-European applicants are targeting a foreign market. Comparisons are nevertheless justified and informative, since even European patent applicants only use the EPO if they are targeting a market that goes beyond their domestic one. Otherwise they would most probably file a patent application with their national patent office only.

In line with the EPO's official reporting method for annual statistics, the reference year used for all statistics is the application year, which is either the filing year of the European patent application (for applications filed direct with the EPO (Article 75 EPC)) or the year of entry into the European phase (for international (PCT) patent applications (Article 158(2) and Rule 107 EPC)). Each EP application identified as relevant for AM technologies is assigned to one or more sectors, or fields of the cartography, depending on the technical features of the invention.

Where necessary, the dataset was further enriched with bibliographic patent data from PATSTAT, the EPO's worldwide patent statistical database, as well as from internal databases, providing additional information, for example, about the names and addresses of applicants and inventors.

In addition, information was retrieved from Bureau van Dijk's ORBIS Version 2019 database, which was used to harmonise and consolidate applicant names and identify their type and industrial sector (NACE Rev. 2). Where there were multiple applicants, one of them was selected, with priority given to those available in ORBIS. Further details on these data are provided in Annex A.

3. Global patenting trends

3. Global patenting trends

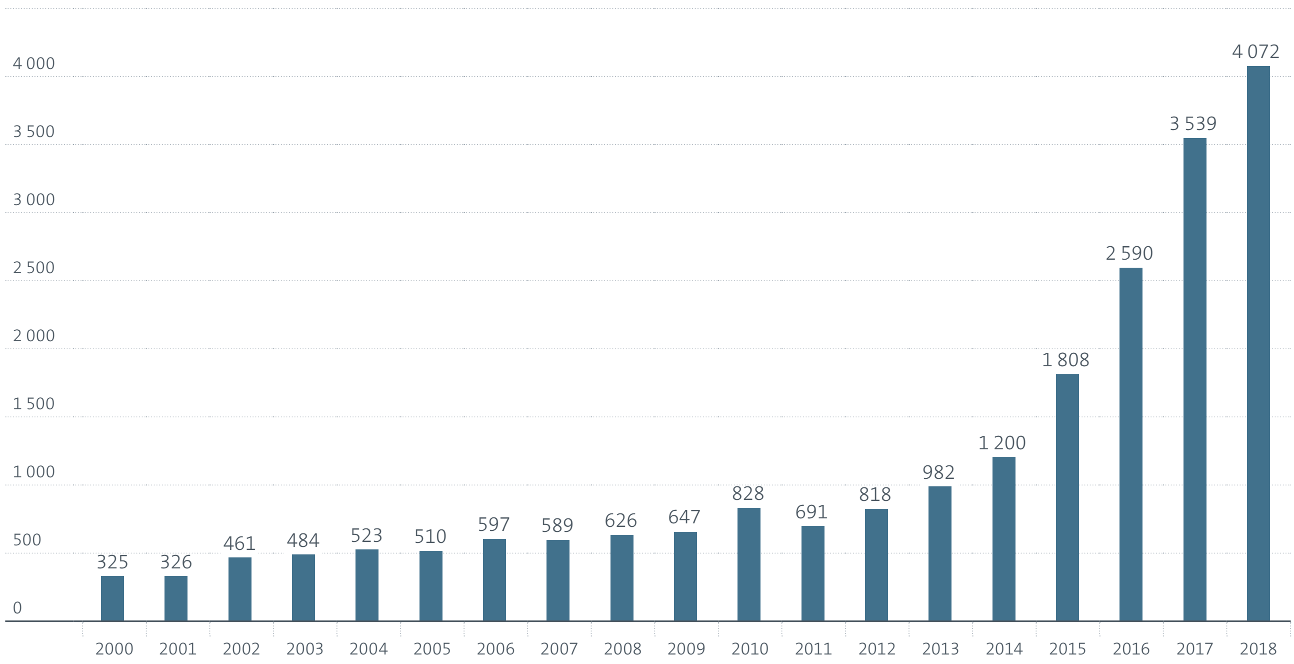
Based on the cartography of AM technologies described in the previous chapter, a total of 21 616 published and unpublished European patent applications were identified with an application date between 2000 and 2018. This chapter presents the general trends in these patent applications, as well as trends for the different technology sectors of the cartography.

3.1 General trends

AM patenting activity at the EPO has been steadily increasing over the years, from approximately 325 applications in 2000 to more than 800 in 2010 (see Figure 11). A dip in 2011 was followed by a marked acceleration. In the five-year period between 2014 and 2018, the number of AM patent applications at the EPO rose by 239%, from 1 200 to more than 4 000 applications per year.

Figure 11

Trend in AM patent applications at the EPO, 2000-2018



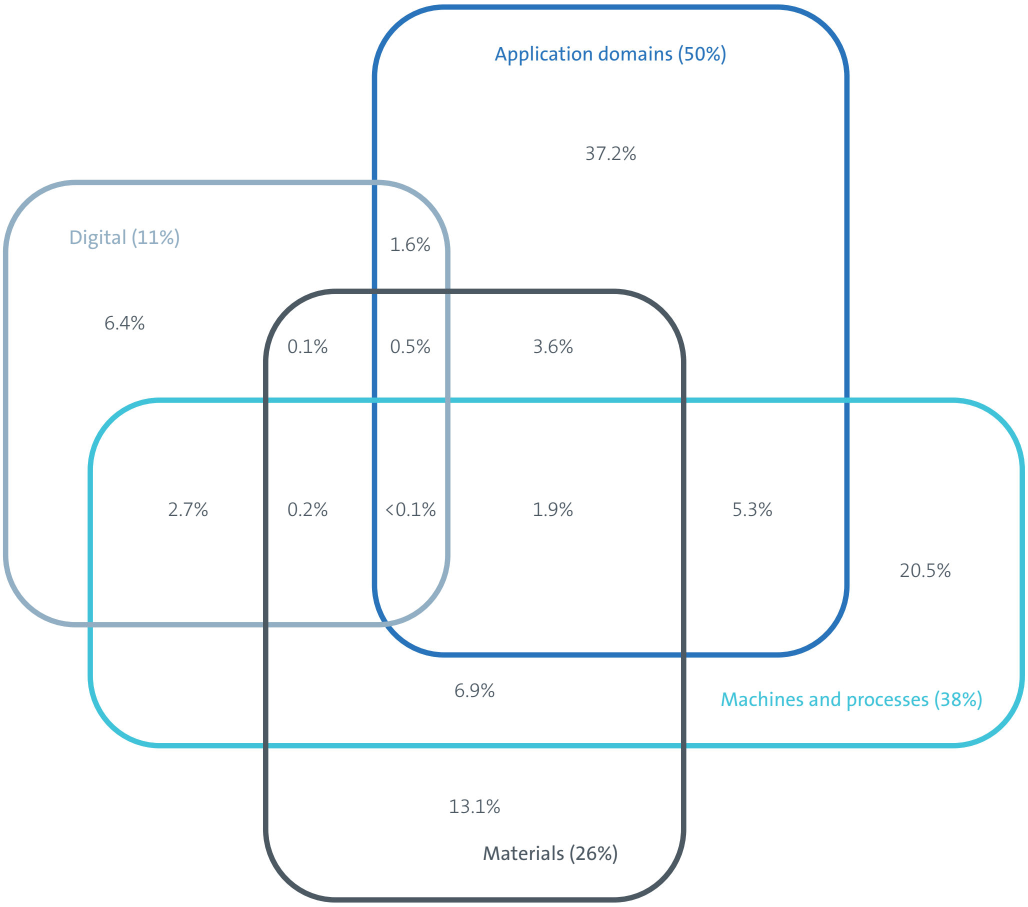
Source: European Patent Office

Of the four AM technology sectors *Application domains* has attracted the largest share (50%) of patent applications at the EPO. *Machines and processes* was the second most important technology sector, with a 38% share of all AM patent applications. Approximately one in four patent applications are related to *Materials*. The group of patent applications related to the *Digital* aspects of AM was the smallest, with 11% of AM patent applications at the EPO between 2000 and 2018.

In many cases, a patent application can cover features of different technology sectors, such that the shares of the four groups add up to more than 100%. For example, an invention can introduce an improvement in a certain material and at the same time describe how it could beneficially be applied in a certain application field. All overlaps of the four AM technology sectors are illustrated in the Venn diagram in Figure 12.

Figure 12

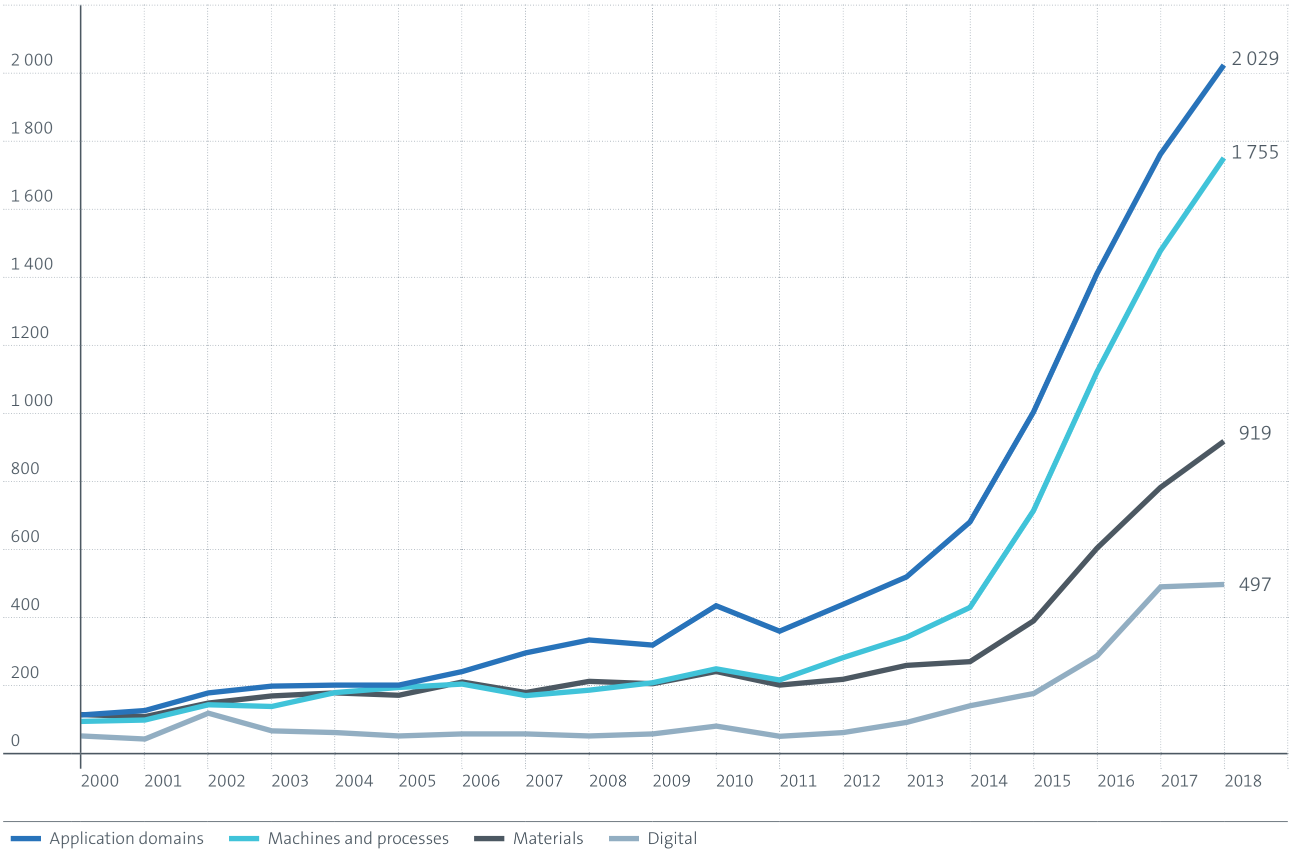
AM patent applications by technology sector, 2000-2018



Source: European Patent Office

Figure 13

Trends in AM patent applications by technology sector, 2000-2018



Source: European Patent Office

Figure 13 shows developments in the four AM technology sectors over the last 20 years. All four of them experienced the strongest growth over the latest five-year period. *Application domains* is the sector that saw the highest absolute increase in patent applications submitted annually between 2014 and 2018. However, in relative terms, the number of EP applications in that sector “only” tripled over the same time period. In comparison, *Materials* and *Digital* saw increases of 240% and 255% respectively, although both started from a lower basis. *Machines and processes*, which was of a similar size to *Materials* until 2011, has seen the highest growth in recent years. Between 2014 and 2018 the annual number of patent applications in this sector grew by more than 300% to over 1 750.

3.2 Trends in AM technology sectors

Figure 14

Trends in AM patent applications by type of material, 2010-2018

	2010	2011	2012	2013	2014	2015	2016	2017	2018
Polymers	165	133	153	171	163	217	350	473	532
Metals/alloys	24	18	22	29	54	82	136	144	219
Ceramics	20	27	24	19	31	66	73	115	114
Biomaterials	27	27	29	35	24	42	69	83	86
Cements	13	5	3	13	14	12	17	18	22

Source: European Patent Office

The AM cartography distinguishes between inventions in five different groups of materials. Figure 14 shows that *Polymers* is by far the largest group, with more patent applications than in the other four groups of materials put together. *Metals/alloys*, currently the second-largest group, has shown the most rapid growth in recent years, with the annual number of patent applications more than tripling between 2014 and 2018. *Ceramics* and *Biomaterials* are the third- and fourth-largest groups and are currently of relatively similar size, although the former has been growing faster recently. *Cements* is by far the smallest group, with just over 100 patent applications submitted altogether in the last ten years.

Figure 15

Trends in AM patent applications by application domain, 2010-2018

Source: European Patent Office

Figure 15 shows developments related to the eight AM *Application domains* in the period 2010 to 2018. More than 4 000 patent applications filed at the EPO were related to *Health*, with more than 900 of them being filed in 2018 alone. *Energy* has become the second-largest domain, with more than 2 000 applications filed between 2014 and 2018. Growth in this field has been very fast, with applications rising from 38 in 2010 to almost 500 in 2017. This was followed by a small decline in 2018. *Transportation* is the third-largest, followed by *Industrial tooling* and *Electronics*.

Although of a relatively similar size, they show somewhat different patterns. While *Transportation* has grown particularly rapidly in recent years, *Industrial tooling* and *Electronics* were already quite large at the beginning of the period in question. *Construction* and *Consumer goods* are still relatively small, when measured by the number of EP applications. However, they are also the ones with the fastest growth. *Food* is by far the smallest of the eight *Application domains*, with approximately 100 patent applications between 2010 and 2018.

Patent applications can contain inventive features relevant to different AM technologies. Where this is the case, the application has been assigned to different fields of the AM cartography, and also possibly to different sectors. Tables 2 and 3 make use of this property to show co-assignments between different types of materials and *Application domains*.[10]

Table 2 presents for each *Application domain* the share of patent applications which have been co-assigned to different *Materials*. It provides an indication of the importance of the five types of material for the particular *Application domain*.

Table 2

Importance of material types for application domain (as % of application domain), 2000-2018

	Health	Industrial tooling	Transportation	Construction	Energy	Consumer goods	Electronics
Polymers	7%	7%	3%	14%	2%	8%	9%
Biomaterials	4%	3%	0%	0%	0%	0%	0%
Metals/alloys	1%	5%	1%	1%	6%	2%	2%
Ceramics	1%	2%	2%	0%	2%	0%	1%
Cements	0%	1%	0%	3%	0%	0%	0%

Note: *Food* is not shown due to the small number of patent applications.

Table 3

Importance of application domains for type of material (as % of material type), 2000-2018

	Health	Industrial tooling	Transportation	Construction	Energy	Consumer goods	Electronics
Polymers	10%	2%	1%	2%	1%	1%	2%
Biomaterials	38%	6%	0%	0%	0%	0%	0%
Metals/alloys	4%	6%	2%	0%	15%	1%	2%
Ceramics	11%	4%	3%	0%	8%	0%	1%
Cements	7%	6%	1%	9%	4%	0%	0%

Note: *Food* is not shown due to the small number of patent applications.

Table 3 takes the opposite approach. For each material, it shows the eight *Application domains* to which the patent applications have been co-assigned. For example, *Polymers* have the most co-assignments in all *Application domains* except for *Energy*, where *Metals/alloys* dominate (Table 2).

This is confirmed in Table 3, which shows that *Health*, the largest of all the *Application domains*, is the most relevant for all material types except *Metals/alloys* and *Cements*. For *Metals/alloys*, most patent applications are co-assigned to *Energy*, while for *Cements*, it is obviously *Construction*.

10 Although this analysis provides interesting insights into the interplay between *Materials* and their *Application domains*, it is merely a snapshot of current developments and relies heavily on the co-assignment of patent applications to different patent classes. It also reflects the difference in size of the *Materials* groups and *Application domains*.

4. Applicants of AM inventions

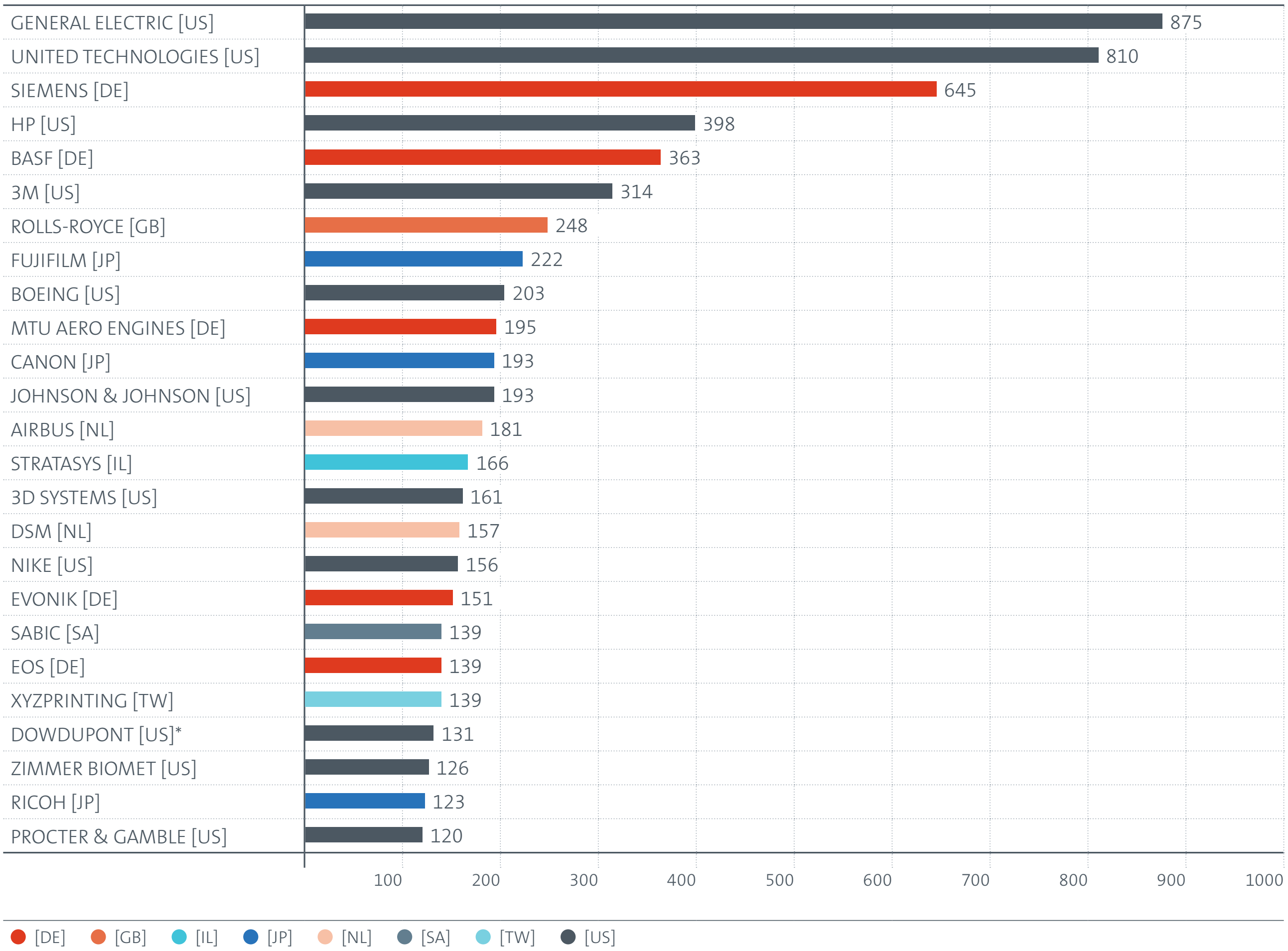
4. Applicants of AM inventions

This chapter focuses mainly on the applicants of AM patent applications. It presents their origin and profiles and the role they play for the different technology sectors.

4.1 Top applicants

Figure 16

Top 25 AM applicants at the EPO, 2000-2018



Source: European Patent Office

* DowDuPont was dissolved into three separate companies in 2019. For the purpose of this study the old company name is used.

The top 25 AM applicants at the EPO in the period 2000-2018 are shown in Figure 16. Together, they filed 30% of all AM patent applications. The analysis is complemented by Figure 17, which shows the trends between 2010 and 2018 for the top 10 applicants. They include large companies from a diversity of sectors such as transportation, chemicals and pharmaceuticals, information technology, electronics, imaging and consumer goods, as well as AM specialists such as Stratasys and 3D Systems.

Two US companies, General Electric and United Technologies, are the clear leaders, with 875 and 810 patent applications each, followed by Siemens (645), a German company. Hewlett-Packard (US) and BASF (Germany) follow at numbers four and five. When looking at the dynamics in the last decade, as shown in Figure 17, it can be seen that General Electric, United Technologies and Hewlett-Packard gained their leading positions mostly through patent applications in the last four years (2015-2018), while patent applications by Siemens, 3M, BASF and Rolls-Royce are spread over a much longer time period.

Altogether, the top 25 is made up of companies from eight different countries. The US and Europe dominate, with eleven US companies and eight European ones, five of which are from Germany. Three Japanese companies and one each from Israel, Saudi Arabia and Chinese Taipei complete the top 25 ranking (see Figure 16).

Figure 17

Trends in AM patent applications for the top 15 applicants, 2010-2018

	2010	2011	2012	2013	2014	2015	2016	2017	2018
GENERAL ELECTRIC [US]	19	7	22	23	31	58	142	259	235
UNITED TECHNOLOGIES [US]	3	3	8	4	25	146	229	203	157
SIEMENS [DE]	17	17	29	52	20	59	79	131	174
HP [US]	1	—	1	2	—	13	27	133	178
3M [US]	25	17	21	17	15	21	23	44	40
ROLLS-ROYCE [GB]	19	9	9	9	17	40	33	41	44
BASF [DE]	18	19	15	26	9	19	31	24	36
BOEING [US]	1	2	3	4	20	27	31	46	51
MTU AERO ENGINES [DE]	4	10	15	17	31	33	25	31	13
AIRBUS [NL]	3	6	4	22	15	34	44	17	31
JOHNSON & JOHNSON [US]	9	7	12	29	20	22	23	12	25
NIKE [US]	3	2	9	9	8	16	20	37	49
XYZPRINTING [TW]	—	—	—	—	1	7	24	60	47
SABIC [SA]	4	1	1	4	1	5	21	31	66
CANON [JP]	5	1	1	7	13	19	35	29	22

[DE] [GB] [JP] [NL] [SA] [TW] [US]

Source: European Patent Office

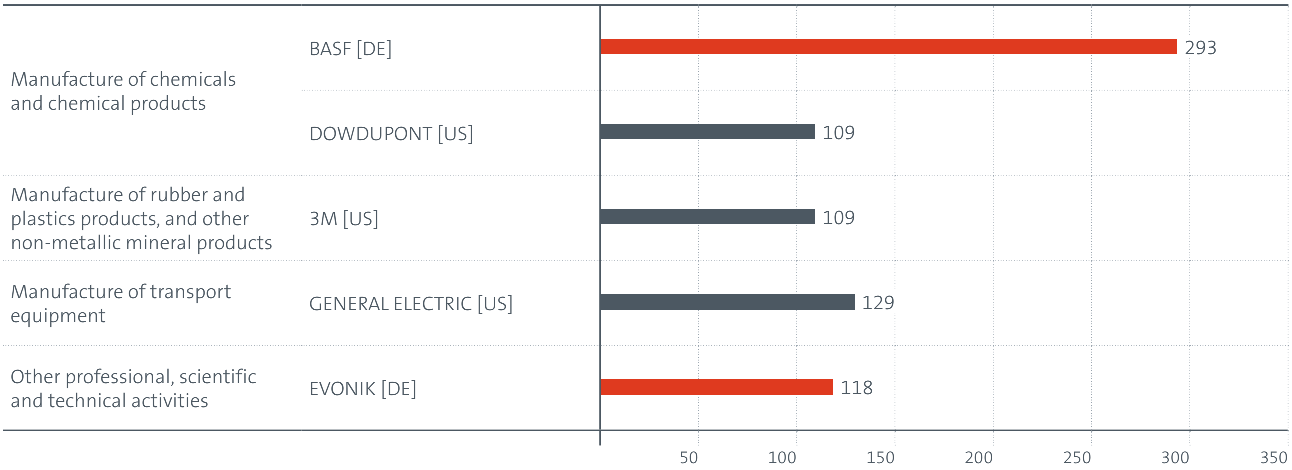
4.2 Top applicants by sectors and fields

Figures 18–21 present the top five applicants in the period 2000-2018 and their core industry activity for the four AM technology sectors.[11] They show that some large companies are actively contributing to several AM sectors, while others specialise in certain technology areas. For example, General Electrics is the only company that appears in the top five of every technology sector, making by far the largest contribution to *Machines and processes*, followed by *Application domains*. United Technologies seems to have a similar profile, although its strength clearly lies in the *Application domains* sector. Siemens likewise appears in the top five lists of all technology sectors, except for *Materials*, where BASF is a clear leader. In *Digital*, Hewlett Packard is the main contributor.

For most AM technology sectors, the industry sector of the company also determines the biggest contributors. *Materials* (Figure 18) is in particular dominated by the chemical industry. In *Digital* (Figure 20), many of the top companies originate from the computer and electronics industry, while equipment and machine manufacturers dominate in *Machines and processes* (Figure 21).

Figure 18

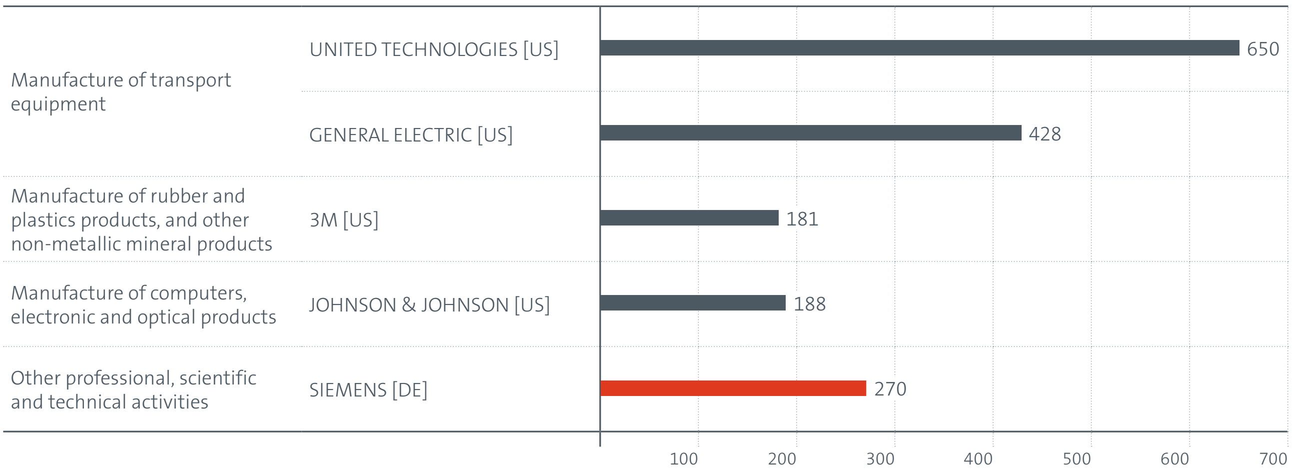
Top 5 applicants – materials, 2000-2018



Source: European Patent Office

Figure 19

Top 5 applicants – application domains, 2000-2018

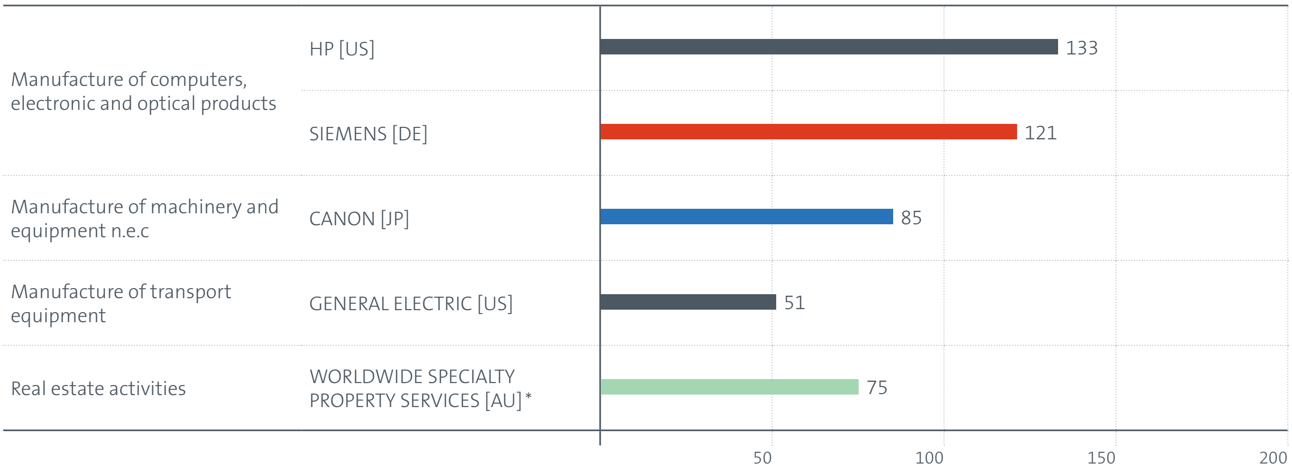


Source: European Patent Office

11 Core industry activity is based on the "intermediate SNA/ISIC aggregation A*38" of core NACE Rev. 2 of each company. The concordance table can be found on p.44 in https://ec.europa.eu/eurostat/documents/3859598/5902521/KS-RA-07-015-EN.PDF.

Figure 20

Top 5 applicants – digital, 2000-2018

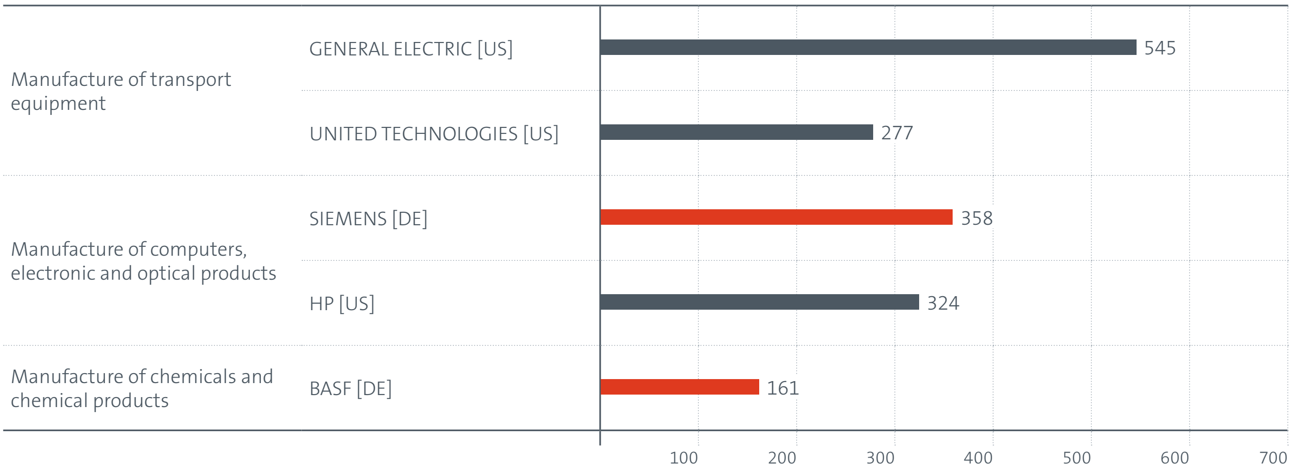


Source: European Patent Office

* Worldwide Specialty Property Services was formerly known as Silverbrook Research.

Figure 21

Top 5 applicants – machines and processes, 2000-2018

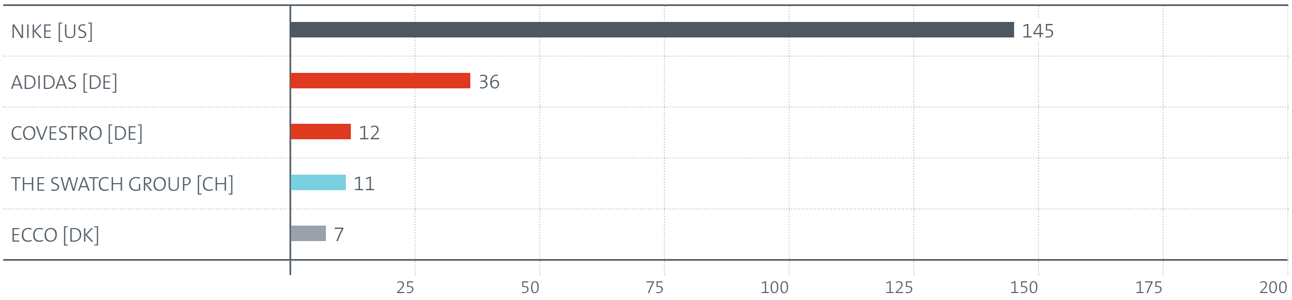


Source: European Patent Office

According to Figure 19, the sector of *Application domains* is also dominated by equipment and machine manufacturers. However, the figure also reveals a diversity of industries for the different *Application domains*. For example, when comparing the top applicants in *Consumer goods* (Figure 22) and *Health* (Figure 23), it is clear that the former is led by sports equipment manufacturers Nike and Adidas, while the latter is led by medical equipment manufacturers such as Johnson & Johnson, Zimmer Biomet and Essilor.

Figure 22

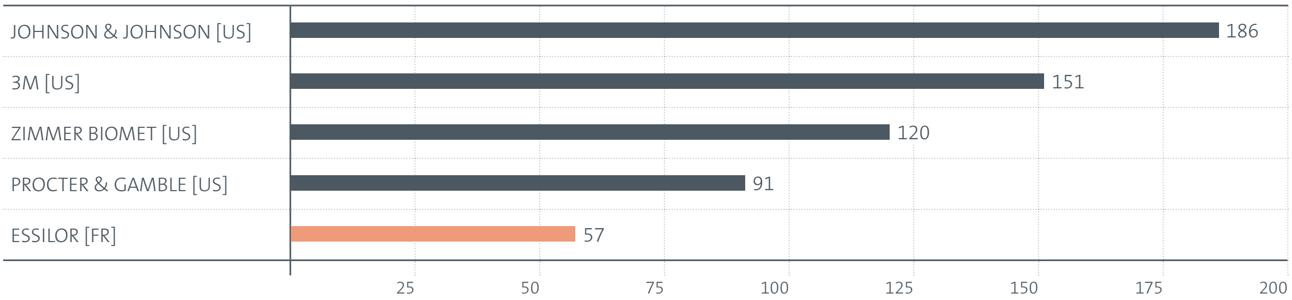
Top 5 applicants – consumer goods (application domains), 2000-2018



Source: European Patent Office

Figure 23

Top 5 applicants – health (application domains), 2000-2018

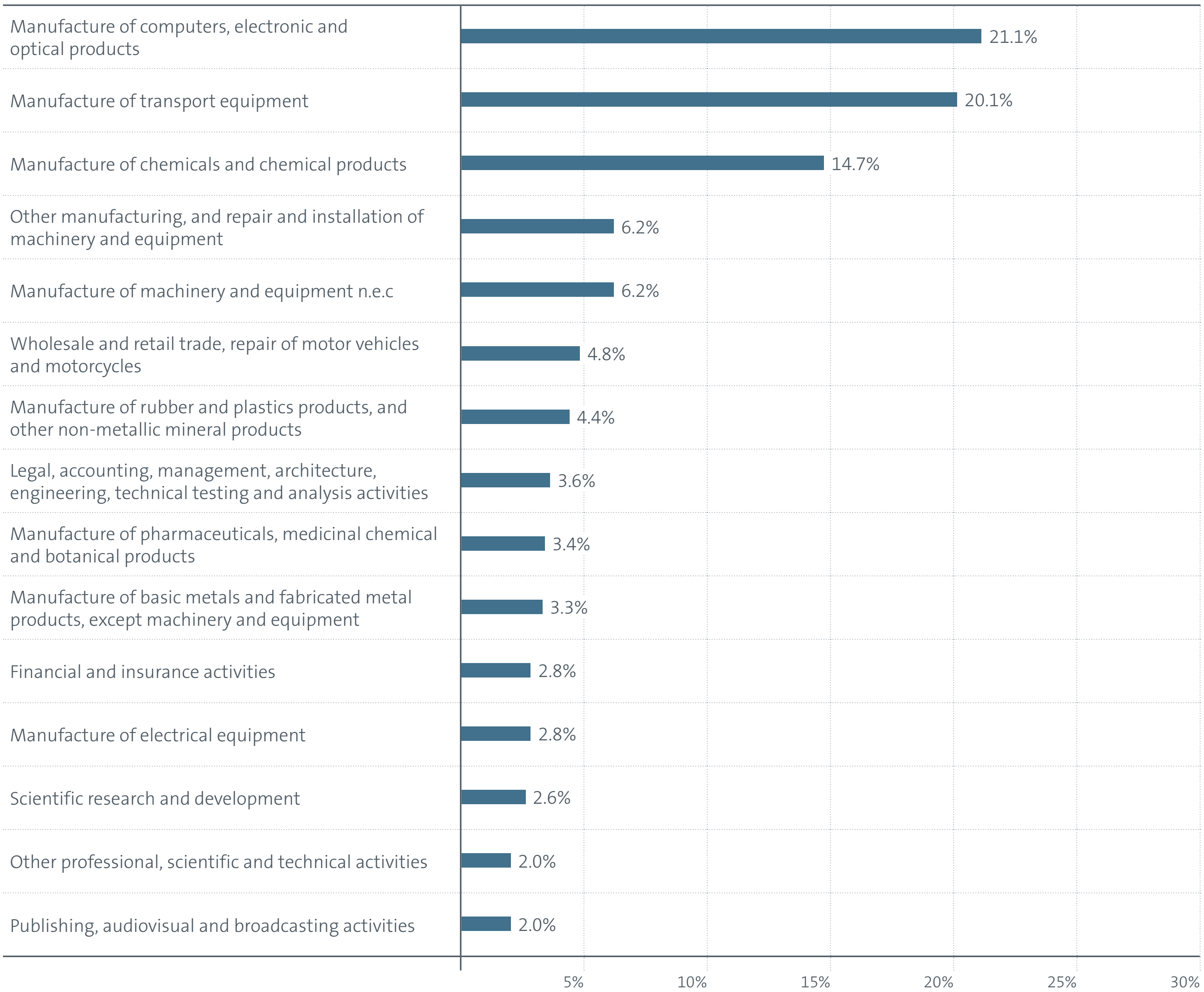


Source: European Patent Office

4.3 Industry profiles and size of AM applicants

Figure 24

AM patent applications by core industry activity of the applicant – top 15, 2000-2018

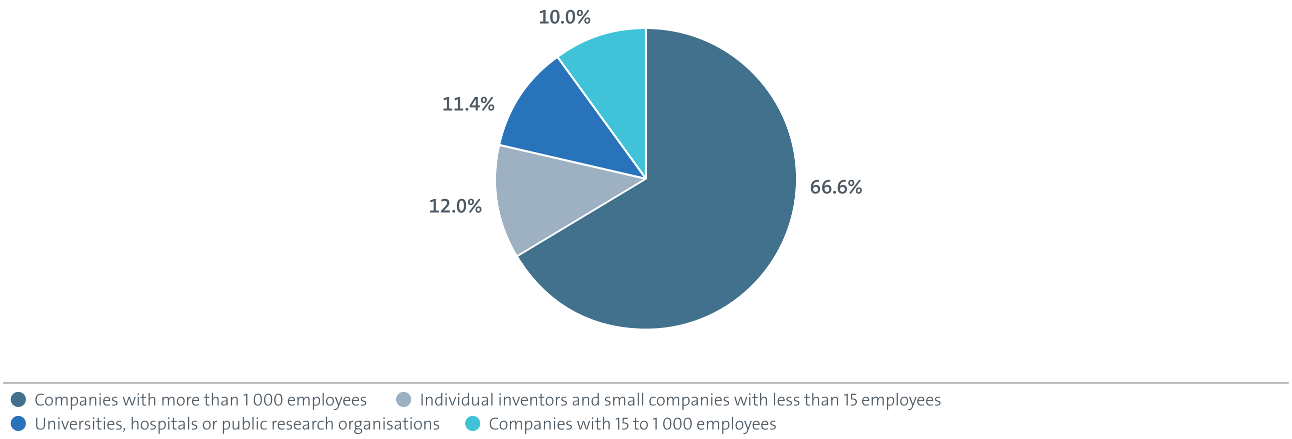


Source: European Patent Office

On an aggregate level, computer and electronics manufacturers (21.1%) together with transport equipment manufacturers (20.1%) contribute the largest share of AM patent applications filed by companies (Figure 24). Together with the chemical industry sector (14.7%), they are responsible for more than half of all AM patent applications at the EPO between 2000 and 2018. Figure 24 shows that although their shares are much smaller, many companies which do not belong to manufacturing industry sectors are also filing significant numbers of AM patent applications.

Figure 25

AM patent applications by applicant type, 2000-2018



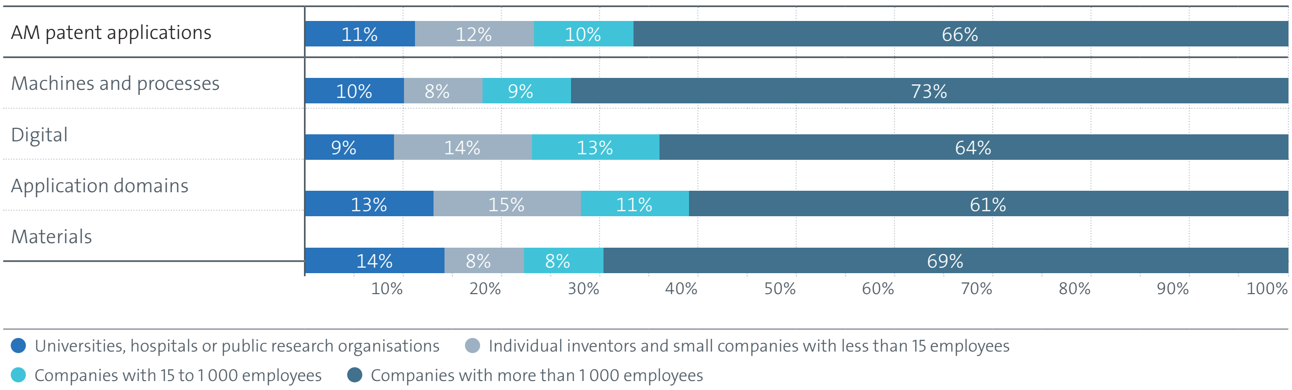
Source: European Patent Office

Two out of three patent applications in AM technologies at the EPO were filed by very large companies of more than 1 000 employees (Figure 25).[12] However, smaller companies, with a combined share of 22%, also contributed significantly to AM inventive activity. 12% of applications in AM technologies were filed by individual inventors or very small companies with fewer than 15 employees, and 10% by companies with 15 to 1 000 employees. Universities, hospitals and public research organisations also contributed heavily to AM innovation and patenting activity. In fact, more than one in ten AM patent applications originates from this group of applicants, and their share has remained relatively stable over the last twenty years.

However, there is some variation across the different technology sectors (Figure 26). The shares of very large companies are highest in *Machines and processes* (73%) and lowest in *Applications* (61%), while the shares of universities, hospitals and public research organisations (PROs) are highest in *Materials* (14%) and lowest in *Digital* (9%). The relative contributions of individual inventors and companies with less than 1 000 employees are high in *Digital* (27%) and *Application domains* (26%) and low in *Machines and processes* (17%) and *Materials* (16%).

Figure 26

AM patent applications by applicant type and AM technology sector, 2000-2018



Source: European Patent Office

12 For the criteria for company categorisation, which is based on thresholds with respect to the number of employees, total assets and operating revenue are described in ORBIS – user guide (https://help.bvdinfo.com/mergedProjects/68_EN/Home.htm). Calculations are based on the variable *Company size categories* of the global ultimate owner in the ORBIS data set or internet search if information was not available.

5. Origins of AM inventions

5. Origins of AM inventions

This chapter analyses the geographic distribution of AM inventions using information about the origin of the inventors disclosed in European patent applications.[13] The focus is on the identification of global AM innovation centres. For the purposes of this chapter, Europe is treated as a single entity, and includes all the EPC contracting states.

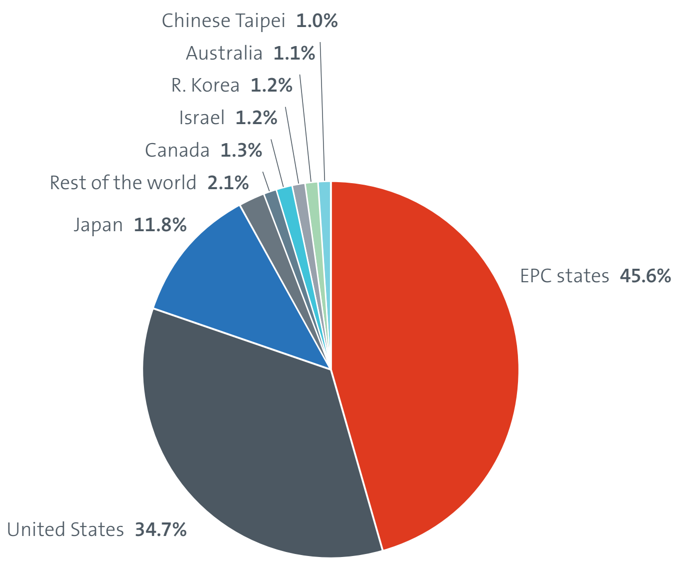
5.1 Global innovation centres in AM

European inventors and US inventors together accounted for four out of five AM patent applications at the EPO between 2000 and 2018 (see Figure 27). Patent applications from both regions grew particularly fast from 2014 onwards (see Fig. 28). Within this five-year period the number of AM patent applications filed increased by 220% to almost 2 000 for European inventors and by 288% to more than 1 400 for US inventors.

Japan, with 12%, is the third-largest country. However, its growth has stagnated somewhat in recent years. The number of Japanese inventions actually fell between 2006 and 2013, before recovering to pass the 300 mark in 2017. Several other countries, such as Canada, Israel, Australia, R. Korea and P.R. China, which in recent years belonged to the largest applicant countries at the EPO, contributed around 1% or less each. Inventors from the rest of the world accounted for only 7% of AM inventions altogether. However, their trend was very positive, and the number of patent applications filed per year increased by 319% between 2014 and 2018 to over 400.

Figure 27

AM patent applications by inventor origin, 2000-2018

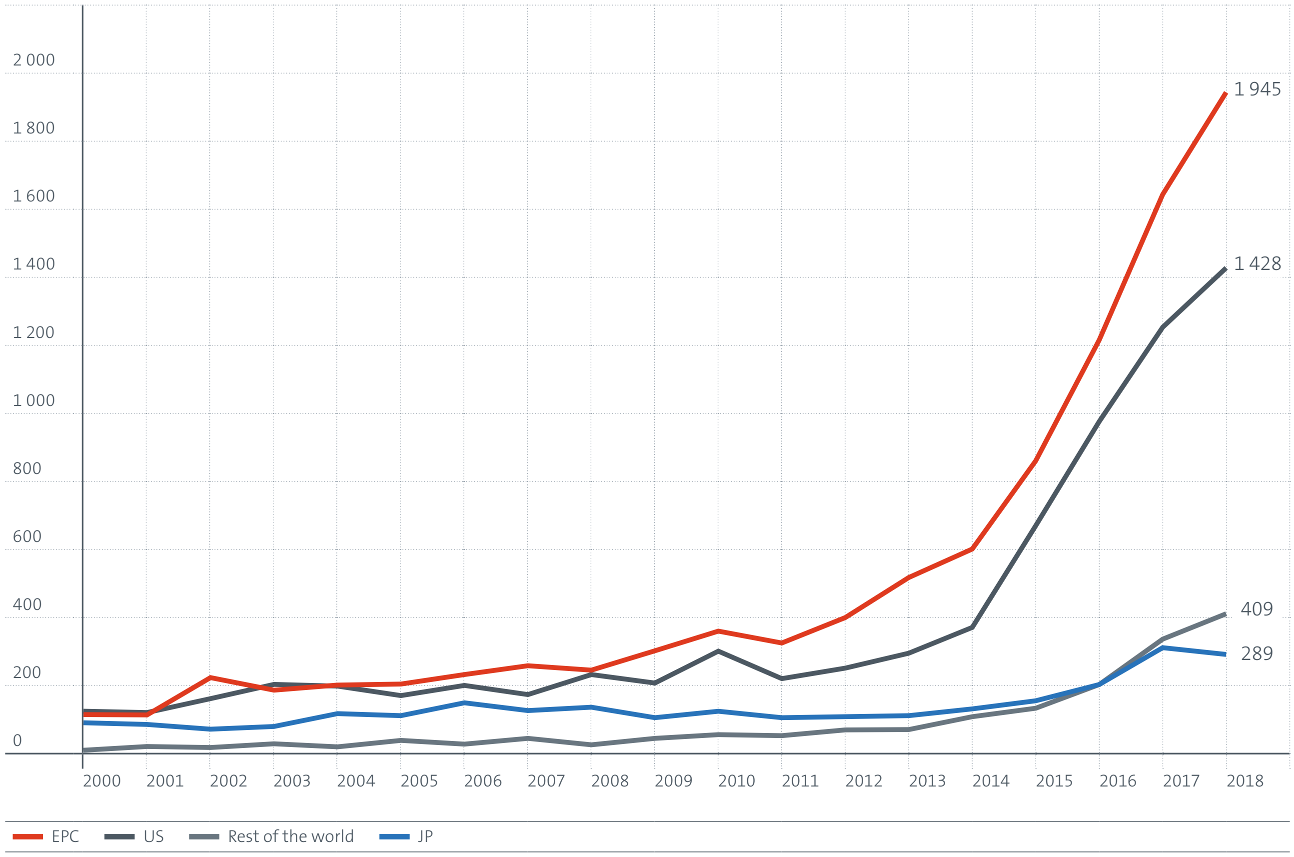


Source: European Patent Office

13 Where multiple inventors were indicated on the patent document, each inventor was assigned a fraction of the patent application.

Figure 28

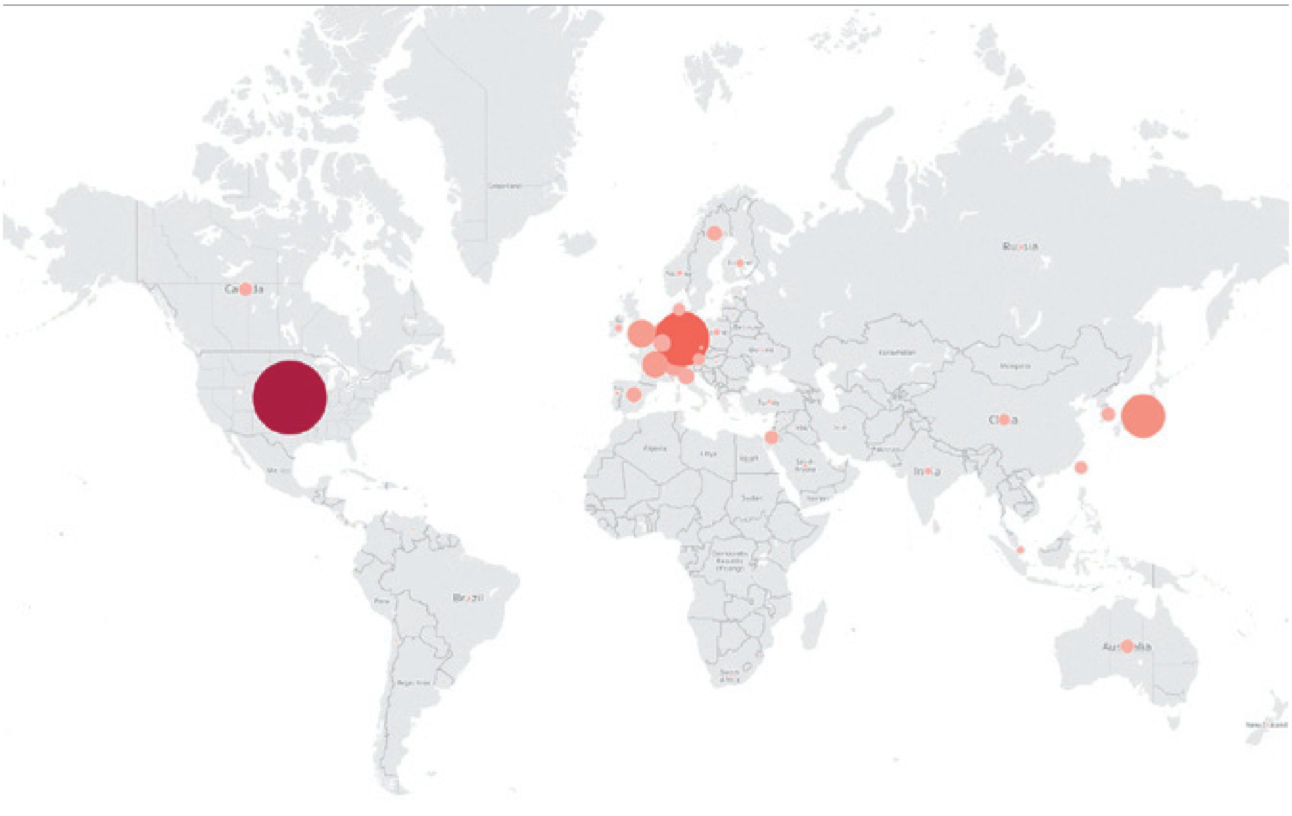
Trends in AM patent applications by inventor origin, 2000-2018



Source: European Patent Office

Figure 29

Worldwide AM innovation centres – global map, 2000-2018



Source: European Patent Office

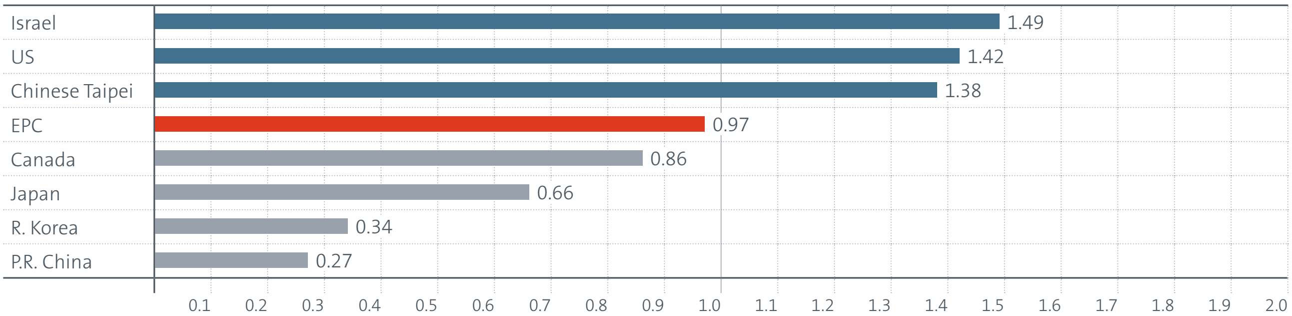
Figure 29 highlights the global AM innovation centres: the larger the circle over the country, the larger that country's contribution to AM inventive activity. It confirms that major AM innovation hotspots can currently be found in Europe, the US and Japan. A number of smaller hubs can be found in other regions, too.

5.2 Revealed technological advantage

The revealed technological advantage (RTA) is a good indicator for measuring a country or region's relative specialisation in a particular technology (Khramova et al, 2013). It complements the share of inventions contributed by a country to patenting in a particular technology by comparing it with the country's total contribution to patenting in all technologies. A figure above 1 indicates a positive specialisation, and below 1 a negative specialisation. If the figure is equal to 1, this means that the country's share in the technology field equals its share in all fields, i.e. there is no specialisation. Figure 30 shows the RTA in AM technologies based on patent applications at the EPO filed between 2010 and 2018 for Europe and seven countries with the largest number of AM patent applications.[14]

Figure 30

Revealed technological advantage (RTA) in AM technologies by country/region, 2010-2018

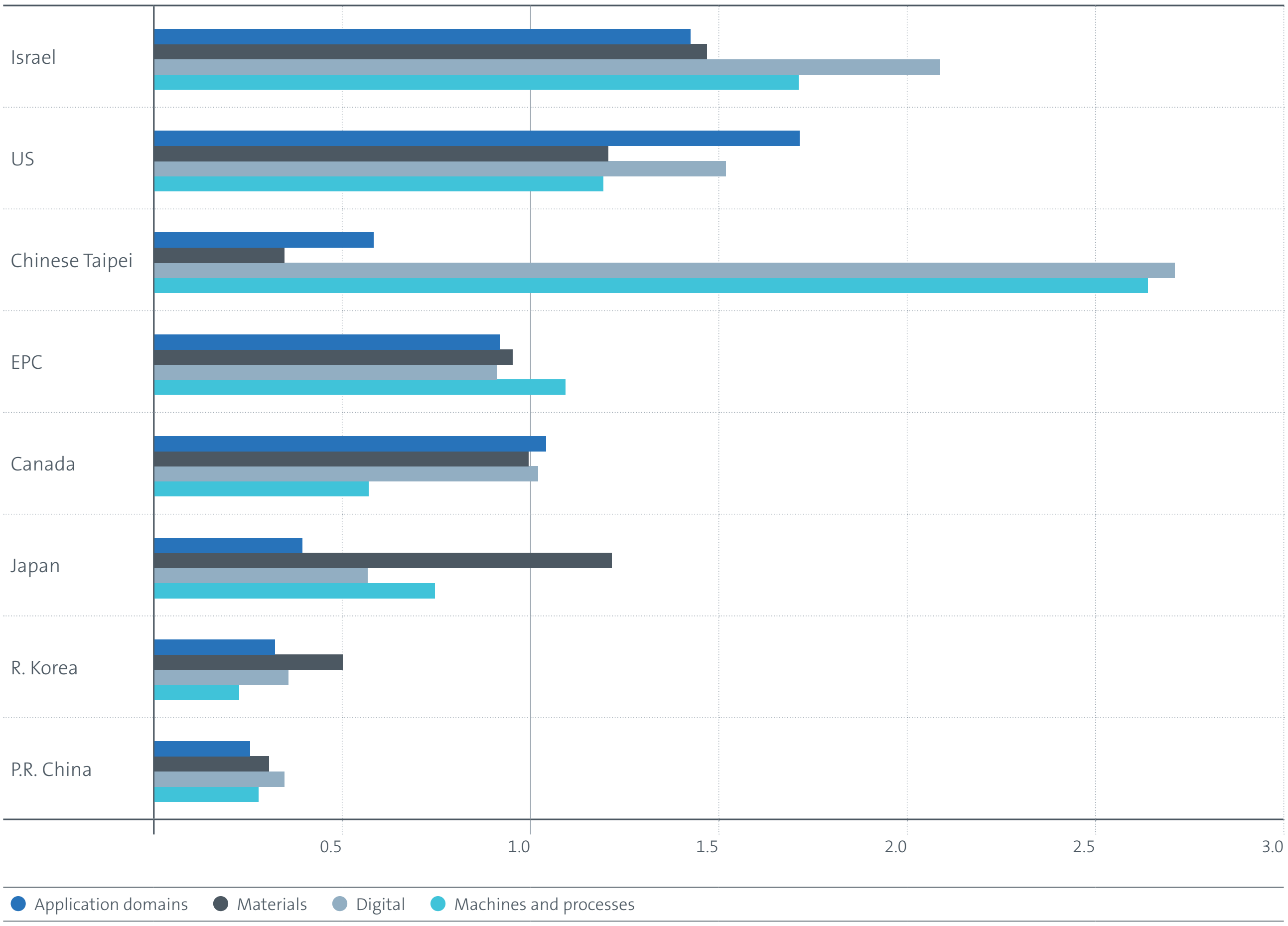


Source: European Patent Office

14 All selected countries have contributed at least 170 European patent applications in the nine-year period 2010-2018.

Figure 31

Revealed technological advantage (RTA) in AM technology sectors by country/region, 2010-2018



Source: European Patent Office

Figure 31 complements the analysis on the level of individual AM technology sectors. According to this indicator, Europe as a region[15] shows a slightly negative specialisation in AM technologies, with an RTA close to 1. The analysis on the level of individual AM technology sectors, however, reveals that Europe shows a positive specialisation in *Machines and processes* (RTA>1), while the indicator is below 1 for all other technology sectors.

Chinese Taipei, the US and, in particular, Israel, with RTAs around 1.5, show a clear positive specialisation in AM technologies. However, while the performance of the US, which shows the strongest specialisation of all countries in *Application domains*, and Israel is quite balanced for all AM technology sectors, Chinese Taipei's specialisation focus – with RTAs above 2.5 – clearly lies in *Digital* and *Machines and processes*.

In contrast, Japan, R. Korea and P.R. China, with RTAs close to or below 0.5, reveal significant negative specialisation in AM technologies. This is confirmed on the level of AM technology sectors, where all the indicators are below 1, with the exception of Japan, which has an RTA above 1 for *Materials*.

15 The contributions of the various EPC contracting states is discussed in the next chapter.

6. European AM innovation ecosystem

6. European AM innovation ecosystem

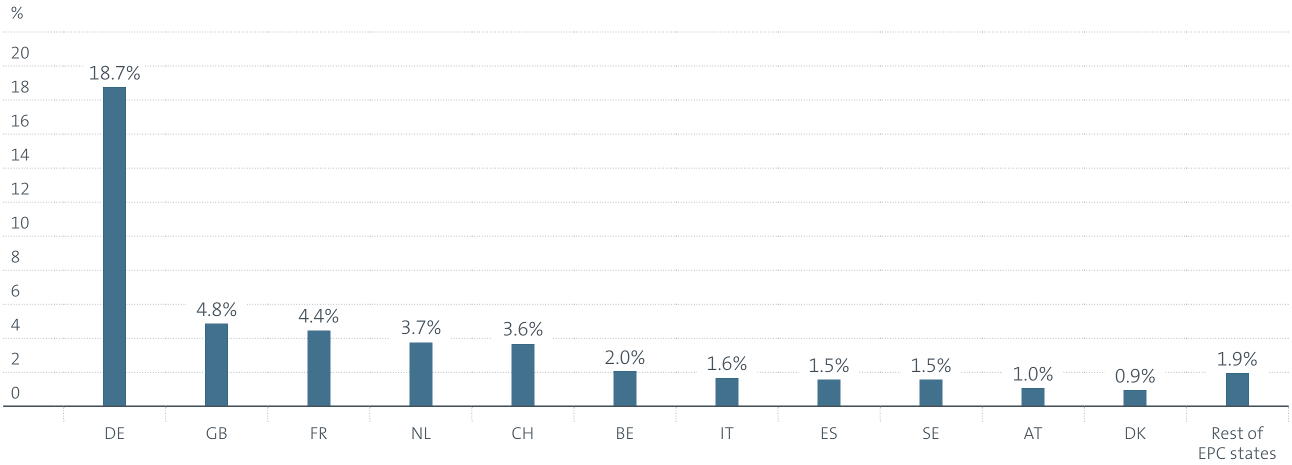
This chapter focuses on patent applications in AM technologies with European inventors, with the aim of assessing the performance of individual EPC contracting states. Where appropriate, comparison is also made with other major AM innovation centres.

6.1 European innovation centres

As reported in Figure 27 above, 46% of AM patent applications at the EPO between 2000 and 2018 were filed by European inventors. Of these, the largest share, at 19%, is attributable to German inventors (see Figure 32).
The United Kingdom (5%), France (4%), the Netherlands (4%) and Switzerland (4%) follow at numbers two to five, with almost equal contributions. The remaining 10% are spread across 28 other European countries.

Figure 32

AM patent applications by country of origin (EPC), 2000-2018

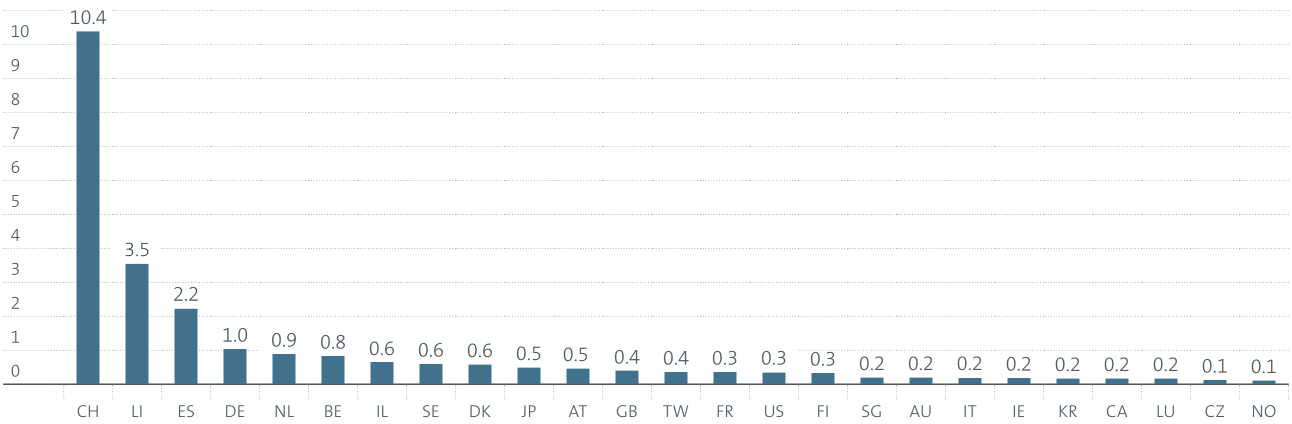


Source: European Patent Office

However, the ranking changes significantly once account has been taken of the size of the economy by dividing the number of AM patent applications by the gross domestic product of a country (see Figure 33). Switzerland moves into first place, with by far the highest number of AM patent applications per euro of economic output, followed by Liechtenstein, Spain, Germany, the Netherlands and Belgium.

Figure 33

AM patent applications (2000-2018) per economic output



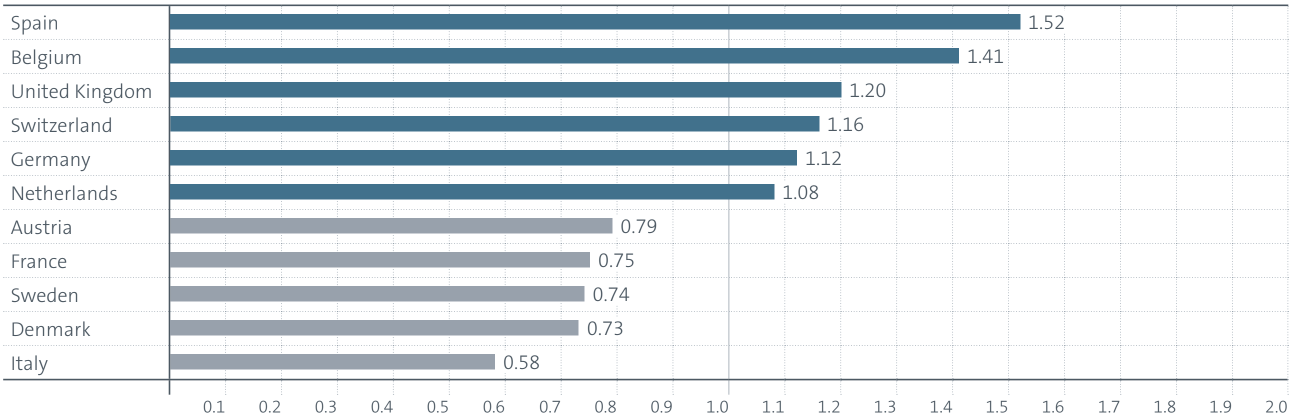
Note: Only countries with at least 10 patent applications in the period 2000-2018 have been considered. Economic output is measured by the countries' GDP in 2018.

Figure 34 shows the relative specialisation in AM technologies of European countries. As presented in Figure 30, the revealed technological advantage (RTA) in AM technologies for Europe as a region was close to 1, showing slightly negative specialisation. However, at country level a more diverse landscape can be observed.

Spain shows the highest degree of specialisation, with an RTA above 1.5 in the period 2010-2018. Hewlett Packard, one of the biggest AM patent applicants (see Figure 16), is expanding its R&D activities in Spain, as illustrated by its recent establishment of a 3D printing and digital manufacturing centre of excellence in Barcelona. It is therefore not surprising that Spain's overall RTA is driven by the *Digital* and *Machines and processes* technology sectors (see Figure 35). Belgium, the United Kingdom, Switzerland, Germany and the Netherlands are the other European countries specialised in AM technologies with an RTA above 1, all of them showing different specialisation profiles on the AM technology sector level. Belgium, the United Kingdom and Germany show positive specialisation in *Application domains*. Of those countries with negative specialisation in AM technologies, only Denmark shows RTAs above 1 in two AM technology sectors: *Application domains* and *Digital*.

Figure 34

Revealed technological advantage (RTA) in AM technologies for European countries (EPC), 2010-2018

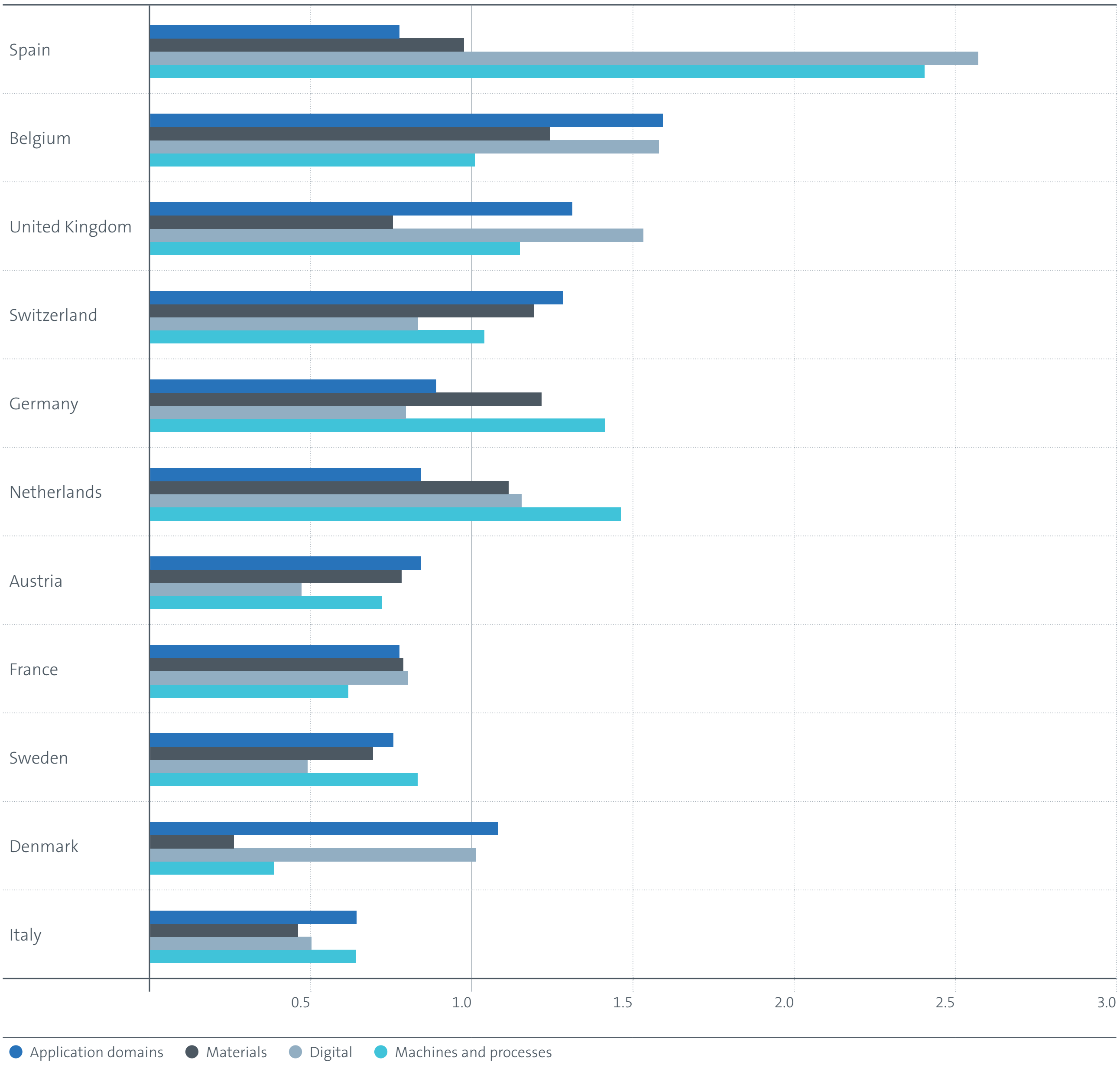


Source: European Patent Office

Note: Only countries with at least 100 patent applications in the period 2010-2018 have been considered.

Figure 35

Revealed technological advantage (RTA) in AM technology sectors for European countries (EPC), 2010-2018



Source: European Patent Office

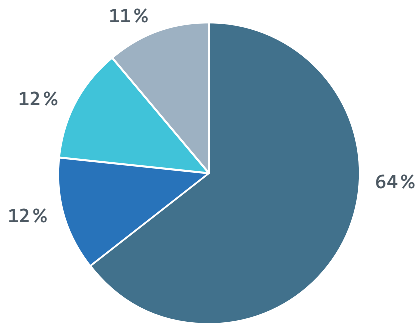
Note: Only countries with at least 100 patent applications in the period 2010-2018 have been considered.

6.2 Profiles of European applicants and inventors

Figure 36 shows the share of AM patent applications by applicant type for European inventions. The distribution of European inventions is very close to the one observed for worldwide AM patent applications (see Figure 25), with roughly two thirds of AM inventions from very large companies (with more than 1 000 employees) and the rest almost equally split between universities, hospitals and public research organisations, individual inventors and small companies with less than 15 employees, and companies with fewer than 1 000 employees.

Figure 36

AM patent applications from European inventors by applicant type, 2000-2018



Companies with more than 1 000 employees Universities, hospitals or public research organisations
Companies with 15 to 1 000 employeess Individual inventors and small companies with less than 15 employees

Source: European Patent Office

The situation is different at country level, as can be seen in Table 4. For example, in Sweden (77%) and Germany (73%), a larger share of AM inventions is contributed by very large companies. In Denmark (49%) and Italy (41%) their share is below 50%, while small companies and individual inventors, and companies with 15 to 1000 employees are responsible for 41% and 49% respectively. With more than 20%, France and the Netherlands see the highest shares of AM inventions contributed by universities, hospitals and public research organisations.

Table 4

AM patent applications by inventor origin and applicant type, 2000-2018

Country	Individual inventors and small companies with less than 15 employees	Companies with 15 to 1 000 employees	Companies with more than 1 000 employees	Universities, hospitals and public research organisations
Germany	8%	10%	**73%**	9%
United Kingdom	14%	8%	**63%**	14%
France	13%	10%	**56%**	20%
Netherlands	8%	9%	**62%**	21%
Switzerland	14%	14%	**58%**	13%
Belgium	9%	8%	**68%**	14%
Italy	26%	23%	41%	9%
Spain	8%	15%	**65%**	11%
Sweden	11%	10%	**77%**	1%
Austria	14%	14%	**56%**	13%
Denmark	16%	25%	49%	10%
EPC	**11%**	**12%**	**64%**	**12%**
US	14%	9%	**66%**	10%
Japan	3%	3%	**86%**	7%
Canada	32%	13%	36%	17%
Israel	27%	17%	46%	9%
R. Korea	9%	13%	**59%**	19%
Australia	22%	36%	22%	19%
Chinese Taipei	3%	4%	**83%**	9%
Total	12%	10%	**67%**	11%

Note: Only countries with at least 100 patent applications between 2000 and 2018 have been considered.

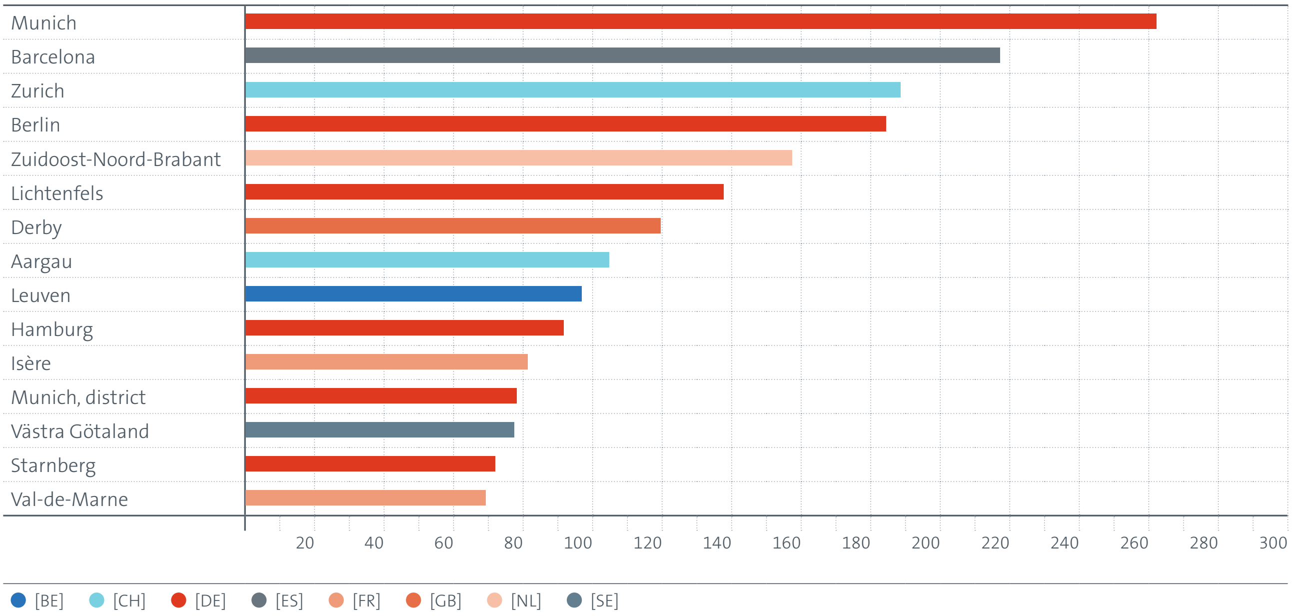
6.3 AM innovation in European regions

This section looks at performance in AM technologies in Europe's regions. Innovation activity is usually concentrated in a small fraction of high-performing regions, even within a country, and a similar pattern applies to AM technologies.

Figure 37 presents the top 15 AM innovation regions in Europe. Regions from eight different European countries are among the 15 largest. Germany clearly dominates, with six regions, including Munich and Berlin, among the top five. Switzerland, with Zurich and Aargau, and France, with Isere and Val-de-Marne, are represented with two regions each, and Spain (Barcelona), the Netherlands (Zuidoost-Noord-Brabant), the United Kingdom (Derby), Belgium (Leuven) and Sweden (Västra Götaland), with one region each.

Figure 37

Number of patent applications by major European AM innovation centres (NUTS 3 regions), 2000-2018



Source: European Patent Office

Table 5

AM technology profiles of major European AM innovation centres (NUTS 3 regions), 2000-2018

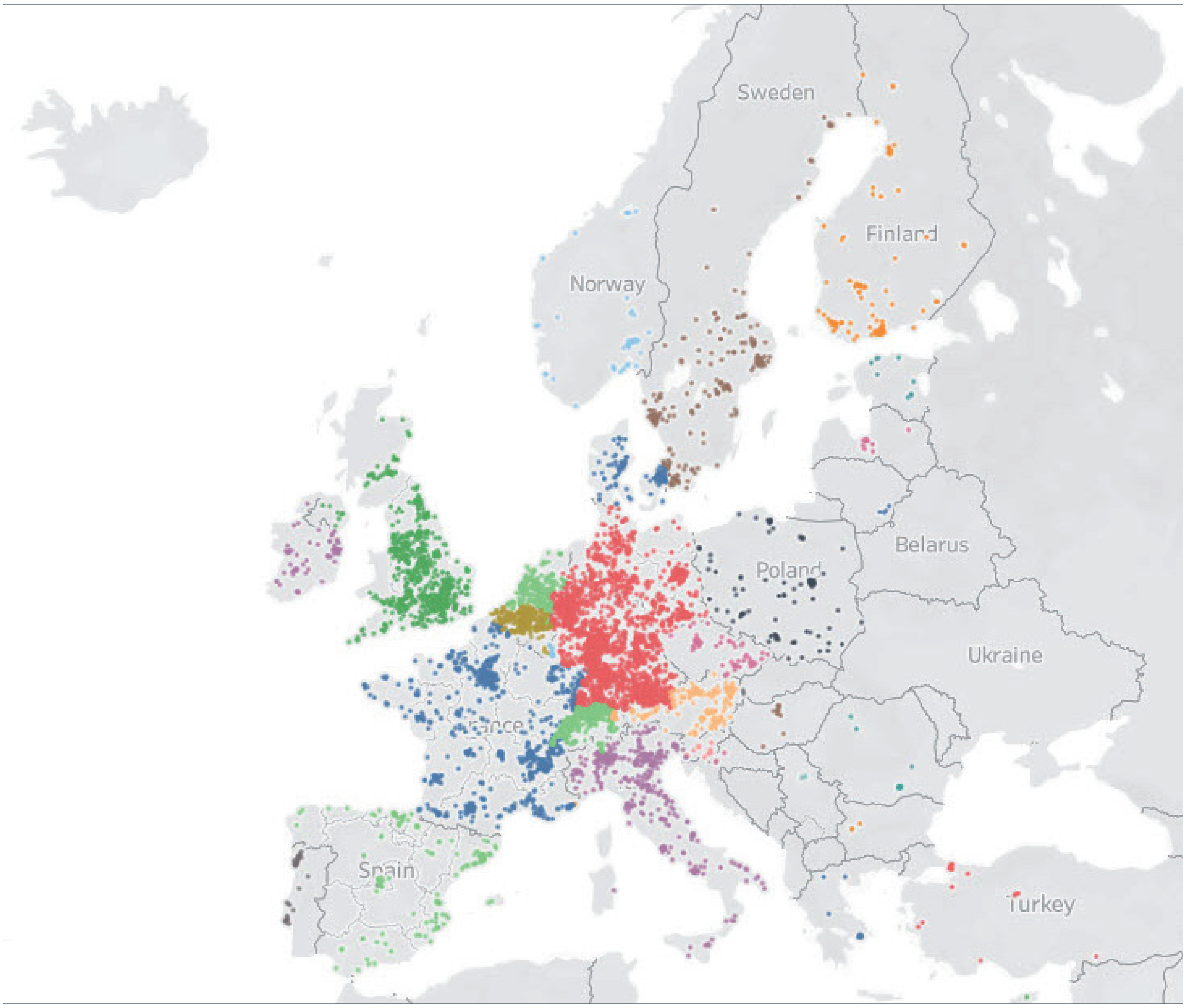
	Region (NUTS 3)	Country	Materials	Applications	Digital	Machines and processes
1	Munich	Germany	1.4%	2.3%	2.6%	3.9%
2	Barcelona	Spain	1.5%	0.5%	4.6%	4.0%
3	Zurich	Switzerland	1.6%	2.5%	2.1%	1.4%
4	Berlin	Germany	0.9%	1.6%	2.1%	2.7%
5	Zuidoost-Noord-Brabant	Netherlands	0.8%	1.6%	1.5%	1.7%
6	Lichtenfels	Germany	0.9%	0.2%	1.3%	3.3%
7	Derby	United Kingdom	0.3%	1.7%	0.5%	1.3%
8	Aargau	Switzerland	1.5%	1.2%	0.3%	1.1%
9	Leuven	Belgium	0.4%	1.3%	2.1%	0.9%
10	Hamburg	Germany	0.6%	1.3%	0.9%	0.7%

Table 5 shows the shares of the patent portfolio of a number of regions in total European patent applications in the four AM technology sectors. It reveals that there are differences between the technology profiles of the regions, which are largely driven by the companies and institutions that are based there. Munich as the top region is relatively strong in all four AM technology sectors, being home to companies such as EOS, MTU Aero Engines, Siemens and Linde. Barcelona is strongly impacted by Hewlett Packard's innovation activities and therefore particularly strong in all AM technology sectors except for *Application domains*. Zurich, which is the third-largest region in Europe, is particularly strong in *Application domains*. It has an established network of small companies and entrepreneurs around the technical university ETH Zurich, but also larger companies such as Sonova, a specialist in hearing care solutions.

Despite the strong regional concentration, innovation in AM technologies is observed in almost all European countries, as can be seen on the map of European inventors in Figure 38.

Figure 38

Spatial distribution of European inventors of AM technologies, 2000-2018



Source: European Patent Office

Annex

A. Methodology

A.1 Applicant name and entity type

Information retrieved from Bureau van Dijk's ORBIS Version 2019 database was used to harmonise and consolidate applicant names and identify their type and industrial sector (NACE Rev. 2). Where there were multiple applicants, one of them was selected, with priority given to those available in ORBIS.

Applicant name

The following rules were applied after matching of applicant names to ORBIS:

1. Take the global ultimate owner (GUO) of the applicant.
2. If GUO not available, take applicant name matched to ORBIS.
3. For the remaining applications, take first applicant and manually clean names in accordance with available ORBIS (GUO) company names.

Entity type

Using information in ORBIS and PATSTAT (TLS206_PERSON), the following rules were applied to assign patent applications to the following categories:
(a) individual inventors and small companies with less than 15 employees;
(b) companies with 15 to 1 000 employees;
(c) companies with more than 1 000 employees;
(d) universities, hospitals and public research organisations.
In all steps additional manual checks were carried out.

1. Categorise all patent applications as *Universities, hospitals and public research organisations* if there is at least one applicant of type GOV NON-PROFIT, UNIVERSITY or HOSPITAL according to PATSTAT or as identified manually through a keyword list with manual checks (UNIV, ECOLE, HOCHSCHUL, SCUOLA, COLLEGE, INST, POLITEC, HOSPITAL, etc.). In addition, search manually for variations of the top 100 GOV NON-PROFIT, UNIVERSITY or HOSPITAL applicants.

2. For the remaining patent applications, if matched to ORBIS, take company size category, as provided in the dataset – i.e. small company, medium-sized company, large company, very large company – which is based on thresholds with respect to the number of employees, total assets and operating revenue (see ORBIS – user guide https://help.bvdinfo.com/mergedProjects/68_EN/Home.htm).

3. For the remaining patent applications, assign to *individual inventors* if PSN_SECTOR in PATSTAT of all applicants is INDIVIDUAL.

4. The remaining applicants were dealt with manually via online searches.

A.2 Identification of AM patent applications

The cartography was assembled from the intellectual input of patent examiners at the EPO and developed and populated in the following three steps.

Step 1:
Linking the cartography to the patent classification scheme

Technology experts were asked to identify the technologies relevant for additive manufacturing from their areas of expertise and, together with patent classification experts, to provide information about the field ranges of the Cooperative Patent Classification (CPC) scheme in which the inventions of the different technologies can be found. The results were used to create a concordance table of AM technologies and CPC ranges (see Annex B Cartography).

The table contains around 100 different technologies with assigned CPC field ranges in all technical fields and sectors of the AM cartography scheme (see Chapter 2). The cartography and the assignment of CPC ranges were verified by applying ad hoc queries against the EPO's full-text patent database and analysing the results. Anomalies were reassessed by classification experts and corrected/amended where necessary.

Example

Technology	Description	CPC ranges	AM sector
Control and monitoring of particular 3D printing techniques	Controlling particular techniques: laser beam, laser curing, machining, wire, welding, laminated, solid deposit manufacturing, etc.	G05B2219/49011, G05B2219/49013 – G05B2219/49019, G05B2219/49021 – G05B2219/49029, G05B2219/49031 – G05B2219/49039	DIGITAL

Step 2:
Identifying AM patent applications

Upon identification of the relevant technology fields, a distinction has been made between AM-specific classes, such as B29C64 (AM of polymers) or B22F3/1055 (manufacturing of articles from metallic powder by selective sintering), and non-specific ones, such as A61K9 (medicinal preparations). The specific ones have been included in their entirety.
The non-specific ones have been combined with a set of semantic keywords referring to additive manufacturing.
On patent documents in these non-specific classes, full-text search queries were applied to all published (and unpublished EP applications) in the respective CPC ranges in order to identify documents relating to the concepts of additive manufacturing techniques, materials and their applications.
Due to the large variation in AM processes, varying from fused deposition moulding to electron beam melting, the variation in expressions used in the field of AM is large.
Hence, an extensive list of semantic keywords was used in combination with proximity operators in various combinations. The semantic keywords have not been restricted to any specific part of the application. Any occurrence of any of the terms in one of the family members, including translations, was considered valid. Nevertheless, the emphasis was put on retrieving true positives with the highest degree of certainty. Further subqueries were defined where necessary to reduce noise.

Step 3:
Classifying patent applications to the cartography fields

All CPC codes assigned to each identified AM patent application during the patenting process were extracted and combined. The unique CPC classes for each application were then linked to the respective technology fields and sectors of the cartography using the concordance table from step 1. The combination of the cartography fields defined the characteristic AM technology fields and sectors of the patent application.

Example
– CPC codes assigned to patent application: G05B2219/49011, B23K26/342
– Technology sectors linked to patent application: DIGITAL, MACHINES AND PROCESSES

For the purposes of this study, the statistics on AM patent applications were based on a simple count method, reflecting the number of inventions assigned to a particular field or sector of the cartography, independently of whether some of these inventions were also classified in other fields or sectors.

B. Cartography

Cartography sector and field	Ranges of CPC classes (to be combined with General Query)	Specific CPC classes (not to be combined with General Query)	Special treatment
Application domains_ Food	A23G1; A23P20	A23P2020/253	General Query
Application domains_ Food	A23L5		General Query
Application domains_ Food	A23P10; A23P30	A23P2020/253	General Query
Application domains_ Consumer goods	A43B; A43D	A43D2200/60	General Query
Application domains_ Consumer goods	A44C1–A44C27/008		General Query
Application domains_ Health	A46B1/00–A46B17/08;		General Query
Application domains_ Consumer goods	A47C		General Query
Application domains_ Health	A61B5/C NOT A61B5/14/low; A61B5/15/low; A61B17		General Query
Application domains_ Health	A61C13	A61C13/0013; A61C13/0018; A61C13/0019	General Query
Application domains_ Health	A61F5; A61F2/01–A61F2002/018; A61F2/06–A61F2002/077; A61F2/24–A61F2/2496; A61F2/82–A61F2/97; A61F13	A61F2002/30987; A61F2002/30962; A61F2/30942; A61F2002/30943–A61F2002/30952	General Query
Application domains_ Health	A61J1–A61J19/06; A61G1–A61G2220/20; A62B1–A62B99/00		General Query
Application domains_ Health	A61K9; A61K47/00–A61K47/46; A61K31		General Query
Application domains_ Health	A61P		General Query
Materials_ Biomaterials	A61K39; C07K7/00-C07K14/825; C12N15		General Query
Application domains_ Health	A61L27; A61L31; A61L15		General Query
Application domains_ Health	A61M16/06/low; A61M2207/00; A61M2016/0661		General Query
Application domains_ Industrial tooling	B01J8; B01J19		General Query
Application domains_ Industrial tooling	B22C		General Query
Materials_ Metals/alloys	B22F1; B22F9; C22C1/00-C22C49/14		GQ without (elec-tron_beam 2d (or melt+,fus+))
Application domains_ Energy	B23P6/002; B23P6/005; B23P6/007; B23P15/00; B23P15/02; B23P15/04; B23P15/26; B23P15/246; B23P2700/12; B23P23/04		General Query
Application domains_ Industrial tooling	B29C33/38/low; B29C41		General Query
Machines and processes	B29C48		General Query
Application domains_ Consumer goods	B29D35		General Query
Application domains_ Health	B29D11/00		General Query
Application domains_ Transportation	B60W; B60T; B62D; B60G; B60B; B60C; B60K; F02D; F02N; F02P; F02M; F02B; F16D; F01N; F02F; H01T; B60N; B60R; B60H; B60J; B60Q; F21S45; B60D; B62H; B62K; B62M; B62L; B62J		General Query
Application domains_ Transportation	B62K		General Query
Application domains_ Transportation	B63		General Query
Application domains_ Transportation	B64F5/10; B64F5/40; B64C; B64D		General Query
Application domains_ Transportation	B64G1/402; B64G1/405; B64G1/58		General Query
Digital	B81C	B81C2201/0184	General Query
Materials_ ceramics	C03B19		General Query
Materials_ ceramics	C04B35	C04B2235/6026	General Query
Materials_ cements	C04B26/00–C04B32/02; C04B40/00–C04B40/0691	C04C2111/00181	General Query adding (contour w crafting)

Cartography sector and field	Ranges of CPC classes (to be combined with General Query)	Specific CPC classes (not to be combined with General Query)	Special treatment
Machines and processes	C04B35; B22F3; G03F7; G03G15/224; G03G15/6585; G03G15/1625		General Query
Materials_ polymers	(C08F, C08G, C08J, C08K, C08L, C09D, C09J) NOT (B41M OR B44C OR B44D)		General Query
Application domains_ Health	C12M33/00		General Query
Materials_ Biomaterials	C12N5		General Query
Materials_ Biomaterials	C12P19/04		General Query
Materials_ Metals/alloys	C30B29/52; C30B11/08		General Query
Materials_ Polymers	D01D – D01F13/04		General Query
Materials_ Polymers	D06L – D06Q1/14		General Query
Application domains_ Construction	E01D; E21D9/00 – E21D13/00; E01C		General Query
Application domains_ Construction	E04		General Query
Application domains_ Industrial tooling	E21B		General Query
Application domains_ Energy	F01D		General Query
Application domains_ Energy	F02C7/12/low; F02K1/12/low; F02C7/04/low; F02K3/06;F02K1/822;F02K1/827		General Query
Application domains_ Construction	F16L		General Query
Applicatio domains_ Energy	F28F; F28C; F28D		General Query
Machines and processes	G02B6/12 – G02B6/138		General Query
Application domains_ Health	G02C5/008; G02C7/022		General Query
Materials_ Polymers	G03G9/087/low; G03G9/09/low; G03G9/097/low		General Query
Digital	G03H1		General Query
Digital	G05B19	G05B2219/49002 – G05B2219/49009; G05B2219/49011; G05B2219/49013 – G05B2219/49019; G05B2219/49021 – G05B2219/49029; G05B2219/49031 – G05B2219/49039	General Query
Digital	G06F3/12/low; G06F21; G06F30		General Query
Machines and processes	G06F3/12		General Query
Digital	G06Q30; G06Q20; G06Q10		General Query
Digital	G06T17/00; G06T17/10; G06T17/20; G06T17/005; G06T19/00; G06T19/20; G06T1; G06F15; G06F16		General Query
Application domains_ Health	G09B23		General Query
Application domains_ Energy	H01F41/02; H01F41/04		General Query
Machines and processes	H01J37		General Query
Application domains_ Electronics	H01L24; H01L21/56		General Query without (laser 2d manufact...)
Application domains_ Energy	H01M2; H01M4		General Query
Digital	H04N1/00, H04N1/40, H04N1/46		General Query
Application domains_ Health	H04R25		General Query
Application domains_ Electronics	H05K1; H05K3	H05K3/4664; H05K3/0014	General Query without (laser 2d manufact...)

General Query in English
(Rapid w prototyp+)
(((or additiv+,layer_wise+,free_form??) w (or manufacturing, manufactured,fabricat+)) NOT (additive? 2d ?manufactured_by)) NOT (additive? 2d manufacturer?)
((or "3D",three_dimension+,3_dimension+,three_D) 2d print+) NOT (fig+ w "3D")
(3OG fused, deposition+,model+)
(3UG fused, filament+,(or deposit+,print+))
(3OG fused, filament+,fabricat+)
(4UG selectiv+,laser+,(or sinter+,fus+,melt+))
(((((((((((((laser 2d (or manufacturing, manufactured,fabricat+)) NOT (laser 2d microscope+)) NOT (laser 2d corporation+)) NOT (laser 2d ablati+)) NOT (laser 2d machin+)) NOT (laser 2d cutting)) NOT (laser 2d ?manufactured_by)) NOT (laser 2d manufacturer?)) NOT (Laser 2d weld+)) NOT (laser 2d cut+)) NOT (laser+ 2d mark+)) NOT (laser 2d trimm+)) NOT (laser 2d chips)) NOT (laser 2d diffrac+)) NOT (laser 2d scan+)
(electron_beam 2d (or melt+,fus+))
Stereo_lithograph+ or mi?ro_stereolith+
Free_form_fabri+
(3OG direct,digital+,manufact+)
(3OG additive+,layer+,manufact+)
(vat_polymeris+ or vat_photo_polymer+)
(drop_on_demand)
(3OG laminat+,object+,manufact+)
(desktop w manufact+)
(4OG laser,engineered, net, shap+)
Robocasting
(binder w jet+)
(4OG powder,bed,(or fusi+,melt+,sinter+))
(3OG plaster_base?,print+)
(3OG laser, metal, form+)
(3OG direct,ink,writ+)
(3OG direct, light, process+)
(3OG two,photon,(or lithograph+,polymeri+))
(4OG continu+,light,interface,produc+)
(3OG direct,energy,deposit+)
Multi_material w jet+
(3OG shaped,metal,deposit+)
(4OG direct, metal,deposit+)
selectiv+ w sinter+

General Query in German
(or additiv+,schichtweis+,freiform+) 2w (or herstell+,fabri+)
((or "3D",drei_dimension+,3_dimension+,drei_D) 2d (or print+,drucken,druck)) NOT (Fig+ w "3D")
(4UG (or selektiv+ , generative+),laser+,(or sinter+,schmel+)) NOT (or Laserstrahlschweiß+, laserschwei+,schmelzschwei+)
selektiv+ w lasersinter+
generativ+ w fertig+
elektronenstrahlschmelz+
Stereo_lithograph+
mi?ro_stereolith+
(3OG direkt,digital+,herstell+)
(2OG (additive+ or generat+),herstell+)
(vat_polymeris+ or vat_photo_polymer+)
(3UG laminier+,objekt+,herstell+)
(bindemittel+ d (or spritz+,jet+))
(4UG pulverbet+,(or schmel+,sinter+))
(3OG laser, metal+, form+)
(3UG direkt, licht, prozess+)
(3UG zwei,photon,(or lithograph+,polymeri+))
(3UG direkt,energ+,deponier+) or direktenergiedeponier+
(Rapid w prototyp+)
(((or additiv+,layer_wise+,free_form??) w (or manufacturing, manufactured,fabricat+)) NOT (additive? 2d ?manufactured_by)) NOT (additive? 2d manufacturer?)
((or "3D",three_dimension+,3_dimension+,three_D) w print+) NOT (fig+ w "3D")
(3OG fused, deposition+,model+)
(3UG fused, filament+,(or deposit+,print+))
(3OG fused, filament+,fabricat+)
(4UG selectiv+,laser+,(or sinter+,fus+,melt+))
(((((((((((((laser 2d (or manufacturing, manufactured,fabricat+)) NOT (laser 2d microscope+)) NOT (laser 2d corporation+)) NOT (laser 2d ablati+)) NOT (laser 2d machin+)) NOT (laser 2d cutting)) NOT (laser 2d ?manufactured_by)) NOT (laser 2d manufacturer?)) NOT (Laser 2d weld+)) NOT (laser 2d cut+)) NOT (laser+ 2d mark+)) NOT (laser 2d trimm+)) NOT (laser 2d chips)) NOT (laser 2d diffrac+)) NOT (laser 2d scan+)
(electron_beam 2d (or melt+,fus+))
Stereolithograph+ or mi?ro_stereolith+
Free_form_fabri+
(3OG direct,digital+,manufact+)
(3OG additive+,layer+,manufact+)
(drop_on_demand)
(3OG laminat+,object+,manufact+)
(desktop w manufact+)
(4OG laser,engineered, net, shap+)
Robocasting
(binder w jet+)
(4OG powder,bed,(or fusi+,melt+,sinter+))
(3OG plaster_base?,print+)
(3OG laser, metal, form+)
(3OG direct,ink,writ+)
(3OG direct, light, process+)
(3OG two,photon,(or lithograph+,polymeri+))
(4OG continu+,light,interface,produc+)
(3OG direct,energy,deposit+)
Multi_material w jet+
(3OG shaped,metal,deposit+)
(4OG direct, metal,deposit+)
(4OG direct, metal,deposit+)

General Query in French

(Rapid? d prototyp+)
((or additiv+,couche+) w (or imprim+,manufact+,fabricat+)) NOT (additive? 2d ?fabriqué_par)
((or "3D",trois_dimension+,3_dimension+,trois_D) 2d (or impress+,imprim+)) NOT (Fig+ w "3D")
impression w tri_dimensionnelle
(fus+ d deposition+)
(3UG fus+, filament+,(or deposit+,fabricat+,print+))
4UG laser+,sélectiv+, (or fritt+,fus+,fond+)
(5UG electron,faisceau+, (or fond+,fus+))
Stéréolithograph+ or mi?ro_stéréolith+
(3UG fabric+,form+,libre+)
(3UG direct+,digital+,(or fabricat+,manufact+))
(3UG additive+,couch+,(or fabric+,manufact+))
(vat_polyméris+ or vat_photo_polymer+)
(3UG lamina+,objet+,fabricat+)
(liant? d jet+)
(4UG poudr+,lit?,(or fusi+,fond+,fritt+))
(3UG platre,base?,imprim+)
(3UG laser, métal, form+)
(3UG direct+,encre+,écri+)
(3UG direct+, lumièr+, proce+)
(3UG deux,photon,(or lithograph+,polymeri+))
(4UG continu+,lumièr+,interface,produc+)
(3UG direct+,énerg+,deposit+)
Multi_matéria+ d jet+
(3UG form+,(or métaux,metal),deposit+)
(((or additiv+,layer_wise+,free_form??) w (or manufacturing, manufactured,fabricat+)) NOT (additive? 2d ?manufactured_by)) NOT (additive? 2d manufacturer?)
((or "3D",three_dimension+,3_dimension+,three_D) w print+) NOT (fig+ w "3D")
(3OG fused, deposition+,model+)
(3UG fused, filament+,(or deposit+,print+))
(3OG fused, filament+,fabricat+)
(3UG sele?tiv+,(or sinter+,melt+),laser+)
(((((((((((((laser 2d (or manufacturing, manufactured,fabricat+)) NOT (laser 2d microscope+)) NOT (laser 2d corporation+)) NOT (laser 2d ablation)) NOT (laser 2d machine)) NOT (laser 2d cutting)) NOT (laser 2d ?manufactured_by)) NOT (laser 2d manufacturer?)) NOT (Laser 2d weld+)) NOT (laser 2d cut+)) NOT (laser+ 2d mark+)) NOT (laser 2d trimm+)) NOT (laser 2d chips)) NOT (laser 2d diffrac+)) NOT (laser 2d scan+)
(electron_beam 2d (or melt+,fus+))
Free_form_fabri+
(3OG additive+,layer+,manufact+)
(drop_on_demand)
(3OG laminat+,object+,manufact+)
(desktop w manufact+)
(4OG laser,engineered, net, shap+)
Robocasting
(binder w jet+)
(4OG powder,bed,(or fusi+,melt+,sinter+))
(3OG plaster_base?,print+)
(3OG direct,ink,writ+)
(3OG direct, light, process+)
(3OG two,photon,(or lithograph+,polymeri+))
(4OG continu+,light,interface,produc+)
(3OG shaped,metal,deposit+)
(4OG direct, metal,deposit+)

C. European patent applications in AM technologies by country of origin using fractional counting, application years 2000-2017

Country	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
United States	121	117	158	200	195	167	197	170	229	204	298	217	248	292	368	668	975	1253
Germany	50	48	78	80	77	81	98	127	120	137	151	146	191	250	219	346	504	611
Japan	87	82	68	76	114	108	146	123	133	102	121	102	105	108	128	152	200	309
United Kingdom	17	15	21	13	24	24	23	22	20	33	34	35	35	46	77	81	137	183
France	6	12	11	15	16	13	21	14	19	19	34	30	25	46	55	101	105	180
Netherlands	6	4	12	12	11	15	25	18	20	31	23	18	22	34	62	91	125	131
Switzerland	11	9	20	24	27	21	22	21	17	19	27	28	48	43	55	74	91	94
Belgium	7	8	7	9	5	16	12	17	12	22	27	14	20	27	42	31	49	52
Spain	2	2	1	0	2	1	3	1	3	3	5	6	6	4	8	19	24	91
Italy	4	2	3	6	8	4	9	11	9	7	15	7	11	22	17	28	47	76
Sweden	3	0	3	10	7	10	4	7	6	13	19	14	11	9	27	25	37	54
Israel	2	1	5	1	3	10	3	7	3	1	14	8	19	13	9	19	32	48
Korea, Republic of	0	3	4	2	1	5	8	6	3	7	6	12	8	16	25	24	31	41
Canada	2	3	2	9	7	10	2	11	5	9	6	4	8	9	20	20	40	61
Chinese Taipei	0	0	0	0	0	0	0	1	1	3	1	0	2	4	9	13	33	72
Austria	4	2	3	3	1	3	2	3	5	3	6	9	5	9	4	18	24	52
China	0	0	0	0	1	0	0	1	2	5	7	5	3	5	10	13	24	44
Denmark	1	7	2	7	3	5	7	6	6	11	10	7	18	14	19	18	10	22
Australia	1	5	58	7	14	4	3	3	4	5	4	2	7	11	12	9	24	32
Finland	0	1	0	2	2	1	3	2	2	4	2	3	4	1	4	4	15	23
India	0	0	0	1	0	0	2	0	0	0	0	4	0	0	2	5	12	18
Poland	0	0	0	0	0	1	0	0	0	0	2	0	1	3	2	5	6	15
Singapore	0	0	2	1	0	1	5	4	1	2	8	3	2	2	2	4	10	9
Ireland	0	0	1	2	0	1	3	5	2	5	4	4	0	1	3	6	4	8
Norway	0	0	0	1	0	2	0	2	2	0	0	1	2	2	1	5	2	11
Czech Republic	0	0	0	1	0	1	0	0	0	1	0	0	5	1	2	2	3	2
Russia	0	1	0	0	0	0	0	1	0	0	0	0	2	2	3	3	4	4
Turkey	0	0	0	0	0	1	0	0	0	0	0	0	2	0	1	1	4	6
Liechtenstein	0	0	1	0	0	1	0	1	2	0	1	2	2	0	3	2	0	3
Portugal	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	6	1	1
Saudi Arabia	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	2	2
Brazil	0	0	0	1	0	0	0	1	0	0	0	1	0	1	1	3	1	1
New Zealand	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	3	2	2
Luxembourg	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	3	1	1
Hungary	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	1	3
South Africa	0	0	1	0	0	0	0	0	0	0	0	2	0	0	3	0	1	2
Estonia	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	1	0	2
Romania	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
Malaysia	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
Greece	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	2	1	0

Note: All numbers are rounded to the nearest integer.

References

AMFG (2019), "The Additive Manufacturing Industry Landscape 2019: 171 Companies Driving The Industry Forward", https://amfg.ai/2019/02/27/additive-manufacturing-industry.landscape-2019/.

Businesswire (2019), "Global 3D Bioprinting Market Outlook, 2019-2024 – Market Anticipated to Reach $1.64 Billion by 2024", ResearchAndMarkets.com", https://www.businesswire.com/news/home/20191009005386/en/Global-3D-Bioprinting-Market-Outlook-2019-2024.

Chen Zhangwei, Ziyong Li, Junjie Li, Chengbo Liu, Changshi Lao, Yuelong Fu, Changyong Liu, Yan Li, Pei Wang, Yi He (2019), "3D printing of ceramics: A review", Journal of the European Ceramic Society 39 (2019) 661-687.

EPO (2017), "Patents and the Fourth Industrial Revolution", epo.org/trends-4IR.

EPO (2017), "EPO SME case studies", epo.org/sme.

Kačarević ŽP, Rider PM, Alkildani S, et al. (2018) "An Introduction to 3D Bioprinting: Possibilities, Challenges and Future Aspects". Materials (Basel), 11(11):2199, doi:10.3390/ma11112199.

Karzyński, K., Kosowska, K., Ambrozkiewicz, F., Berman, A., Cichoń, J., Klak, M., Serwańska-Świętek, M., Wszola, M. (2018) "Use of 3D bioprinting in biomedical engineering for clinical application" Wykorzystanie biodruku 3D we współczesnej inżynierii biomedycznej i medycynie. Medical Studies. 34. 10.5114/ms.2018.74827.

Khramova, E., Meissner, D., Sagieva, G. et al. (2013) "Statistical patent analysis indicators as a means of determining country technological specialisation", Science, Technology and Innovation WP BRP 09/STI/2013.

Kritikos, M. (2018) "3D bio-printing for medical and enhancement purposes: Legal and ethical aspects", In-Depth Analysis, European Parliamentary Research Service, Scientific Foresight Unit, ISBN 978-92-846-3148-3.

Marketsandmarkets (2016) "4D Printing Market worth $537.8 Million by 2025" https://www.marketsandmarkets.com/PressReleases/4d-printing.asp.

Mason, J., Visintine, S., Quay, T. (2019) "An Overview of Clinical Applications of 3-D Printing and Bioprinting", Ottawa: CATH; CADTH Issues in Emerging Health Technologies; Issue 175.

Murphy, S., Coppi, P., Atala, A. (2019) "Opportunities and challenges of translational 3D bioprinting". Nature Biomedical Engineering. 10.1038/s41551-019-0471-7.

Smartech Publishing https://www.smartechanalysis.com/reports/ceramics-additive-manufacturing-markets-2017-2028/.

Varkey, M., Visscher, D.O., van Zuijlen, P.P.M. et al. (2019), "Skin bioprinting: the future of burn wound reconstruction?." Burns & Trauma 7, Art. 4. https://doi.org/10.1186/s41038-019-0142-7.

Vermeulen, N., Haddow, G., Seymour, T. et al. (2017) "3D bioprint me: a socioethical view of bioprinting human organs and tissues", Journal of Medical Ethics, vol. 43, issue 9, p. 618-624.

Wang, Jia-Cahng, Hitesh Dommati, Sheng-Jen Hsieh (2019) "Review of additive manufacturing methods for high-performance ceramic materials", The International Journal for Advanced Manufacturing Technology (2019) 103:2627-2647.

Xianbin Du (2018) "3D Bio-Printing Review", IOP Conf. Ser.: Mater. Sci. Eng. 301 012023.

Published and edited by
European Patent Office
Munich
Germany

Authors
Judy Ceulemans, Yann Ménière, Aliki Nichogiannopoulou,
Javier Pose Rodríguez, Ilja Rudyk (EPO)

AM cartography
Judy Ceulemans (EPO)

AM case studies
4D printing: Nigel Clarke (EPO)
Bioprinting: Heidi Van den Bulcke, Melanie Geuer, Andreas Przykutta (EPO)
Ceramics: Judy Ceulemans, Ilja Rudyk (EPO)

Design
PD Communication (EPO)

Photos
Cover: Getty Images
p. 25: Courtesy of ICD, https://www.arch2o.com/4d-printing-redefining-materials-material-behaviour/
p. 26-27: Adapted from Fred Mills B1M, https://youtu.be/Knx4JTN-ppY
p. 29: Thinkstock
p. 33: 3D-printed bioceramic parts manufactured by Lithoz's additive manufacturing system

The report can be downloaded from:
epo.org/trends-3dp

ISBN 978-3-89605-252-0

Where to get additional help

Visit epo.org

- Patent search at epo.org/espacenet
- European Patent Register at epo.org/register
- Online filing services at epo.org/online-services
- Training at epo.org/academy
- Job vacancies at epo.org/jobs
- FAQs, publications, forms and tools at epo.org/service-support

Subscribe

- Our newsletter at epo.org/newsletter

Visit epo.org/contact

- Contact forms to send enquiries by mail
- Our Customer Services phone number
- Our contact details

Follow us

- facebook.com/europeanpatentoffice
- twitter. com/EPOorg
- youtube.com/EPOfilms
- linkedin.com/company/european-patent-office