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Innovation trends in additive manufacturing

Patents in 3D printing technologies

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Foreword

The rise of additive manufacturing (AM) – more commonly known as 3D printing – is one of the most fascinating developments of the Fourth Industrial Revolution. 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 revolutionary approach to manufacturing is quickly maturing from a niche market to a disruptive force impacting value chains in a wide range of sectors.

As the patent office for Europe, the EPO is uniquely positioned to report on the scope and implications of this technology trend for Europe's economy. We started to do so in 2020 with the first ever landscaping study on patents and AM, offering unique insights into the fast growth of European patent applications in this field. Three years later, our new study takes a global perspective on the 3D printing revolution, using international patent data to highlight the latest developments in AM from around the world and the relative position of European industry in this fast-evolving field.

Overall, the findings point to a world in which the pace of innovation in AM technologies has accelerated dramatically over the past years. Between 2013 and 2020, global patent filings in 3D printing technologies grew at an average annual rate of 26.3% – nearly eight times faster than for all technology fields as a whole! This trend is visible in sectors as diverse as health and medical technologies, transportation, energy and machine tooling, with increasing impact also in electronics, consumer goods, construction or food.

The study reveals a technology leadership amongst companies based in Europe in the global race of AM innovation, alongside those from the United States. This is clearly reflected in the list of the top 20 AM applicants, which features seven European companies from a diverse range of industries. Our patent data further shows that Europe secured four of the top ten spots for research institutions in AM innovation. This bodes well for the future, since technical progress in AM often stems from cutting-edge research performed in universities and public research organisations.

These results confirm the strong dynamics of AM innovation and its ever-growing impact on a broad range of industry sectors. While Europe may not always lead in other areas of digital innovation, our study reveals its strength in additive manufacturing. This is rooted in a vibrant research-industry ecosystem and has the potential to reinforce the long-established industrial pillars of its economy. In additive manufacturing, Europe can be proud to have such a bright future.

António Campinos
President, European Patent Office

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List of abbreviations

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.
ABS	Acrylonitrile butadiene styrene
Al_2O_3	Aluminium oxide or alumina
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.
ARIPO	African Regional Intellectual Property Organization
BJ	Binder jetting
CAD	Computer-aided design. Use of computers to design real or virtual objects.
CAGR	Compound average 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.
DED	Directed energy deposition
EAPO	Eurasian Patent Organization
EPO	European Patent Office
ESPACENET	Free online service from the European Patent Office for searching patents and patent applications. Includes more than 140 million documents.
FDA	US Food and Drug Administration
FFF	Fused filament fabrication
GCCPO	Patent Office of the Cooperation Council for the Arab States of the Gulf
IoT	Internet of things
IP	Intellectual property
IPF	International patent family. Each IPF covers a single invention and includes patent applications filed and published at several patent offices. It is a reliable proxy for inventive activity because it provides a degree of control for patent quality by only representing inventions for which the inventor considers the value sufficient to seek protection internationally. The patent trend data presented in this report refer to numbers of IPFs.
IPR	Intellectual property right
ISO	International Organization for Standardization. International standard-setting body composed of representatives from various national standards organisations.
OAPI	African Intellectual Property Organization
OEM	Original equipment manufacturer
PBF	Powder bed fusion
PC	Polycarbonate
PEEK	Polyether ether ketone
PET	Polyethylene terephthalate

PLA	Polylactic acid or polylactide
POC	Point of care
PP	Polypropylene
PRO	Public research organisation
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.
SLM	Selective laser melting
TPU	Thermoplastic polyurethane
TTO	Technology transfer office
UV	Ultraviolet
ZrO_2	Zirconia

List of countries

AT	Austria
BE	Belgium
CH	Switzerland
CN	P.R. China
DE	Germany
DK	Denmark
ES	Spain
EU27	27 member states of the European Union (post-Brexit)
FR	France
IE	Ireland
IT	Italy
JP	Japan
KR	R. Korea
LI	Liechtenstein
NL	Netherlands
RoW	Rest of world
SE	Sweden
TW	Chinese Taipei
UK	United Kingdom
US	United States

Executive summary

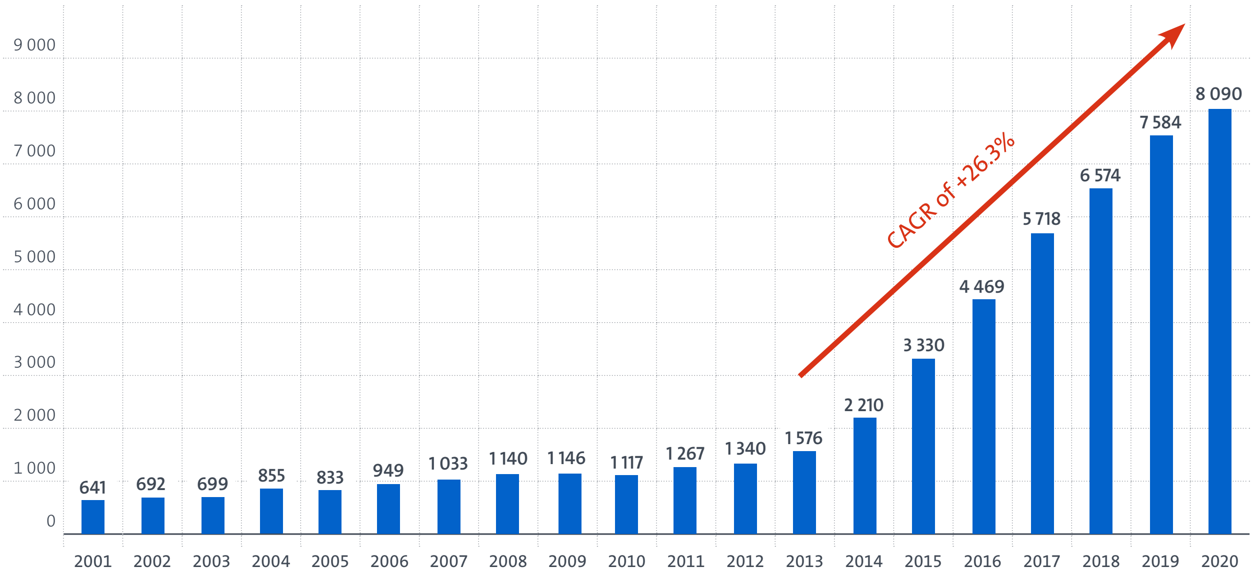
Additive manufacturing (AM), also known as 3D printing, is a revolutionary process that builds three-dimensional objects by adding material layer by layer. In just a decade, it swiftly evolved from a niche use for prototyping to a disruptive force impacting value chains in a growing number of industries. On-going progress in AM technologies keeps expanding the range of opportunities for enhanced customisation, improved production efficiencies and complex designs in those industries. This study uses patent data to shed light on those innovations, thus providing early insights into the forces shaping the future of AM; moreover, the data is vital for understanding the progress of AM and identifying key players driving advancements. Data from patent applications provides valuable insights into AM innovation trends, and this innovation study analyses international patent families (IPFs) to shed light on the current state of AM innovation.[1]

1. Impressive rise of AM innovation

Patent applications from over 50 000 international patent families (IPFs) related to AM technologies have been filed across the world since 2001. Since 2013, their number has surpassed the 2 000 mark annually, with a remarkable compound annual growth rate (CAGR) over 26% over that period (that is eight times the CAGR for patenting overall). Patent applications for more than 8 090 AM-related IPFs were published in 2020 alone, accounting for over 2% of all IPFs.

Figure E1

Trends in IPFs in all additive manufacturing technologies, by earliest publication year



Source: EPO

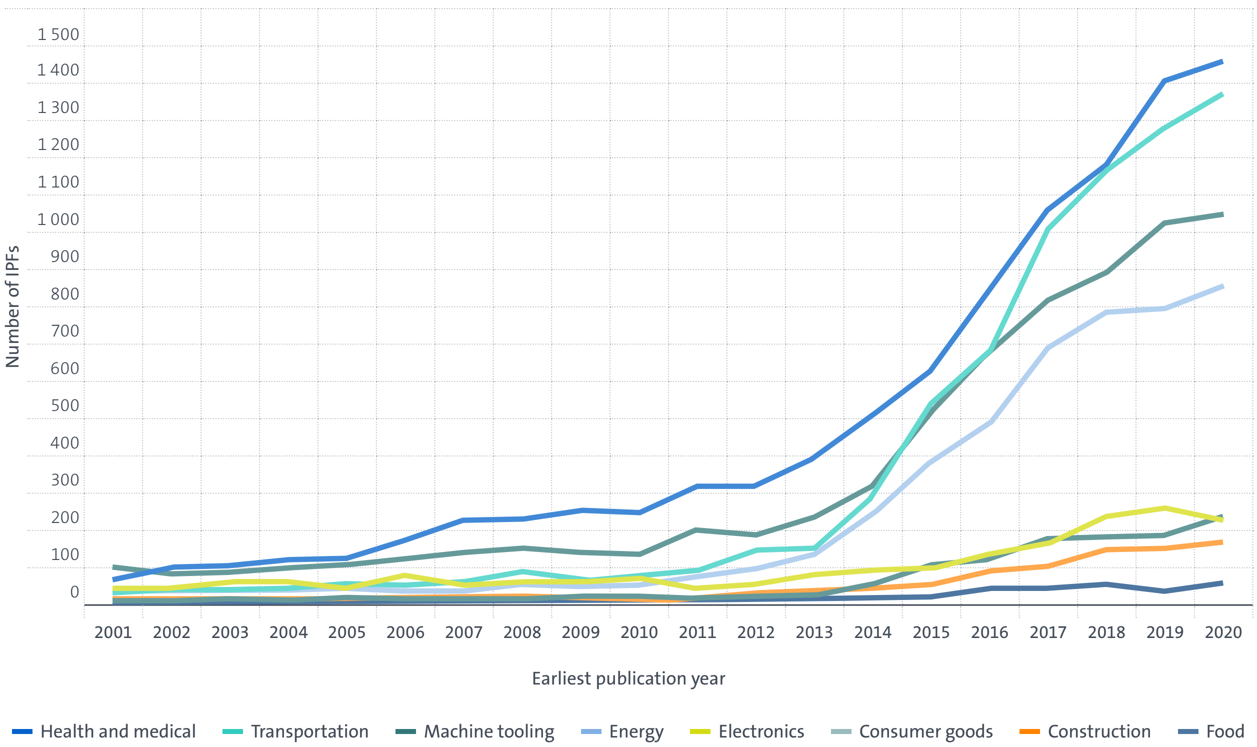
1 Each IPF covers a single invention and includes patent applications filed and published at several patent offices. It is a reliable proxy for inventive activity because it provides a degree of control for patent quality by only representing inventions for which the inventor considers the value sufficient to seek protection internationally. The patent trend data presented in this report refer to numbers of IPFs. See further explanation of IPFs and their usefulness as a metric on page 31.

2. Adoption highest in health and medical, and transportation

While AM has long been instrumental in prototyping, it is now increasingly viable for mass customisation and even serial production. It has gained significant traction in sectors such as health and medical, and transportation (including both aerospace and automotive). In the health and medical sector alone, there were nearly 10 000 IPFs published between 2001 and 2020, as AM's capabilities prove particularly advantageous for patient-specific implants, anatomical models and dental applications. With over 7 000 IPFs, the transportation sector is also witnessing the benefits of AM for product development and advancing toward serial production. Furthermore, valuable applications are emerging in industries like fashion, electronics, construction and even food.

Figure E2

Trends in IPFs in AM application domains, 2001–2020



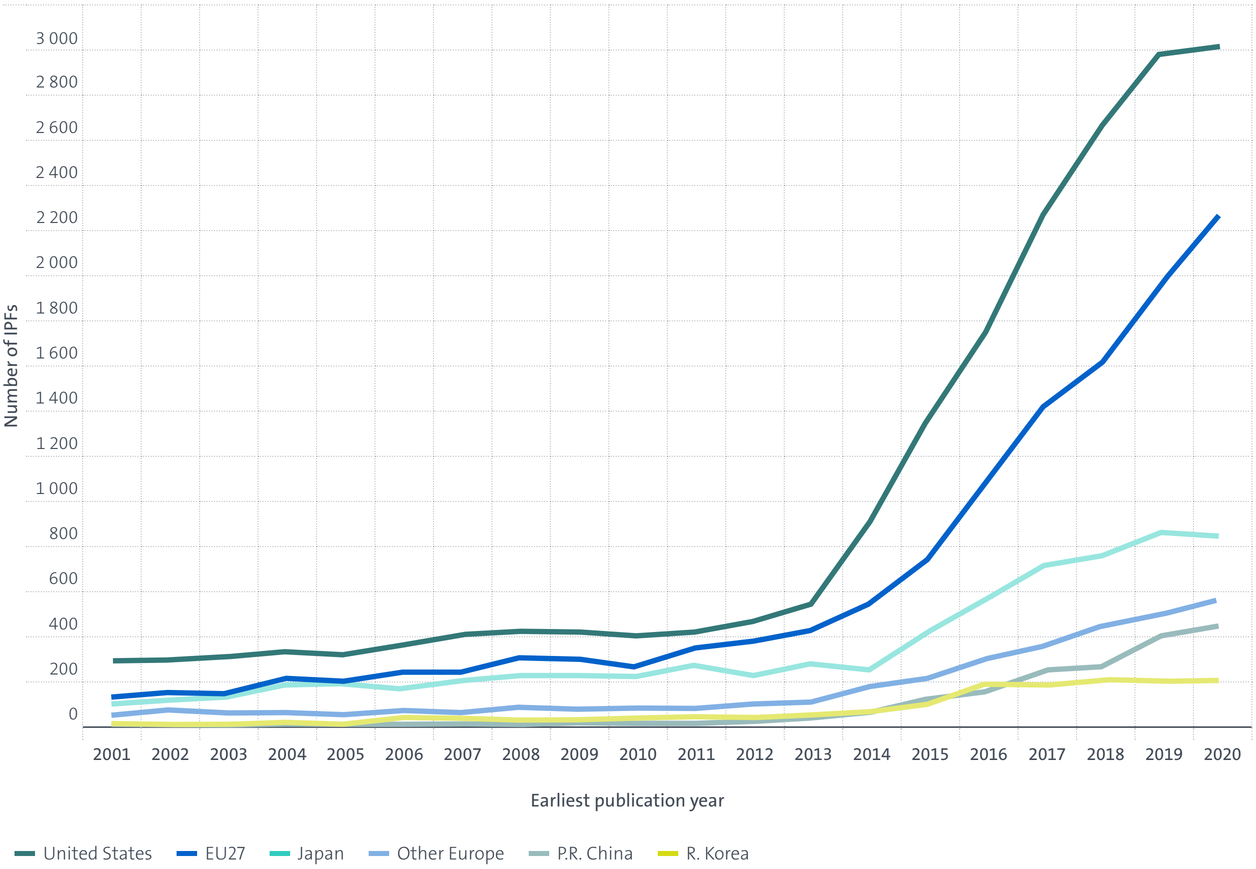
Source: EPO

3. Europe and the US are driving AM innovation

Europe and the US are leading the global race for AM innovation. The US holds the top spot, with 40% of all IPFs related to AM recorded between 2001 and 2020. Europe (EU countries and EPO member states) closely follows with a 33% share. Together, these regions account for an impressive 73% of worldwide AM innovation. In comparison, China and South Korea's contributions remain relatively small at 4% and 3%, respectively. Within Europe, Germany is the strongest contributor, representing 41% of Europe's share, while France has emerged as a notable player with a 12% contribution.

Figure E3

Trends in IPFs in AM technologies by country of origin, 2001–2020



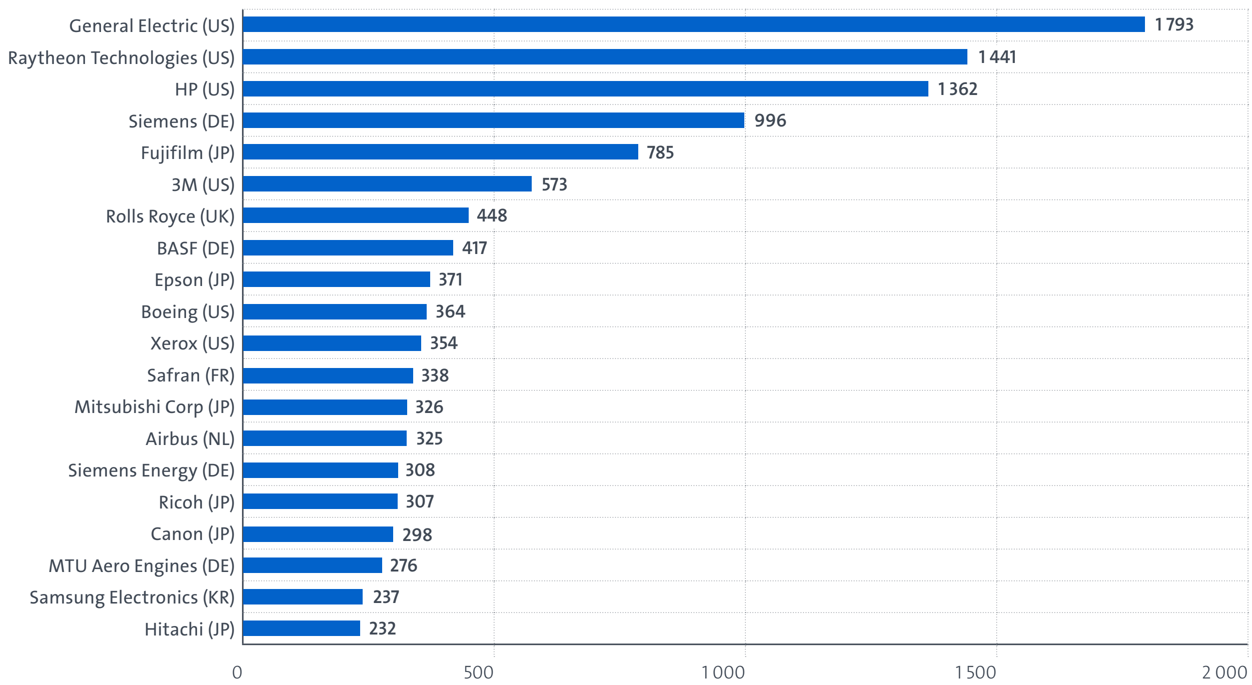
Source: EPO

4. US, European and Japanese companies are in the lead

The analysis reveals that the list of top 20 applicants in AM innovation consists of six US players, seven European companies, six Japanese and one Korean company. Among them, General Electric, Raytheon Technologies, and HP stand out as the companies with the highest number of IPFs between 2001 and 2020. Siemens secures fourth position and emerges as the strongest player from Europe, boasting almost 1 000 IPFs. Although the list of top applicants is dominated by large, international companies from various industry sectors, it also includes several established 3D printing firms and emerging start-ups further down the list. This composition illustrates the rich and diverse landscape of contributors that are actively shaping AM innovation.

Figure E4

Top 20 applicants in AM technologies, 2001–2020



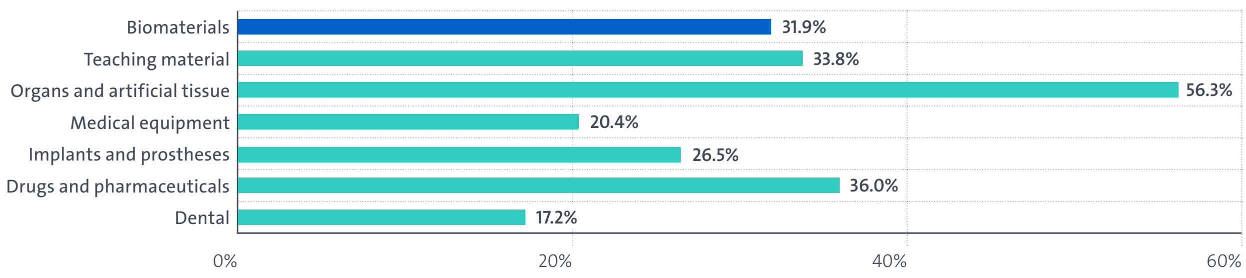
Source: EPO

5. Strong presence of universities and PROs

A remarkably high share (approximately 12%) of IPFs in AM technology have universities and public research organisations (PROs) as applicants, indicating their substantial involvement in advancing the field. However, the presence of universities and PROs varies across different AM technology areas. Particularly in the application domains related to health and medical, their contributions are noteworthy. A university or PRO is behind one in three IPFs associated with biomaterial developments and one in two IPFs for 3D printing of organs and artificial tissue. Their involvement not only enriches the knowledge base, but also fosters ground-breaking advancements in materials, processes and applications within the AM domain and provides a basis for technology start-ups with high growth potential.

Figure E5

Share of universities and PROs in selected AM technologies, 2001–2020



Source: EPO

1. Introduction

Few advancements have generated as much excitement and potential as additive manufacturing (AM), commonly known as 3D printing. This revolutionary technology has swiftly progressed from its early stages of prototyping to become a disruptive force impacting value chains across various industries. As the field of AM continues to evolve at a rapid pace, it is becoming increasingly crucial to conduct studies on the latest developments within this dynamic sector.

Using patent data as a measure of innovation, this study by the European Patent Office is intended to inform decision-makers in both the private and public sectors and the broader public about the technology landscape and most recent trends in additive manufacturing. 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.

1.1 What is additive manufacturing?

Additive manufacturing, also known as 3D printing, is a revolutionary process that builds three-dimensional objects by adding material layer by layer. Unlike traditional manufacturing techniques, which often involve subtractive processes like cutting or shaping material, additive manufacturing starts with a digital design and directly creates the final product by adding material in a controlled manner. This technology allows for the creation of complex and intricate geometries that may be challenging or impossible to produce using traditional methods.

One key difference between additive manufacturing and traditional techniques is the level of design freedom it offers. With additive manufacturing, designers have greater flexibility and can easily create intricate structures, internal channels, and organic shapes without the constraints imposed by traditional manufacturing processes. This allows for the production of highly customised and personalised products that meet specific requirements or individual preferences.

Another differentiating factor is the reduction in waste and material usage. Traditional manufacturing techniques often involve significant material wastage due to the need for cutting, machining, or shaping raw materials. In contrast, additive manufacturing builds objects layer by layer, using only the necessary amount of material required for the final product. This not only reduces material waste but also has potential cost savings in terms of raw material usage.

Furthermore, additive manufacturing enables rapid prototyping and shortens the product development cycle. Traditional manufacturing techniques typically involve lengthy setup times, tooling, and production processes, which can delay the availability of prototypes or new products. Additive manufacturing, on the other hand, allows for quick design iterations and on-demand production, enabling faster product development and time-to-market.

Additive manufacturing is a digital technology because it relies on digital design files and computer-controlled processes to create physical objects. The entire workflow, from initial design to the final production, is based on digital data. Designers use computer-aided design (CAD) software to create 3D models, which are then converted into machine-readable instructions that guide the additive manufacturing machines. This digital nature allows for customisation, complex geometries, and rapid prototyping.

Additive manufacturing is therefore a significant driver of the Fourth Industrial Revolution (EPO, 2020 (b)). It is a key enabler of the digital transformation in manufacturing, bridging the gap between the physical and digital worlds. By integrating additive manufacturing into the production processes, companies can achieve greater efficiency, agility and responsiveness. It enables on-demand manufacturing, reducing inventory and logistics costs. Additionally, additive manufacturing can be integrated with other digital technologies like artificial intelligence, internet of things (IoT) and data analytics to create smart factories that optimise production, enable predictive maintenance and facilitate the customisation of products.

1.2 A maturing technology with disruptive potential

Additive manufacturing has the potential to be highly disruptive from both an economic and business perspective. One of the key advantages is its ability to reduce costs associated with traditional manufacturing techniques. This is because additive manufacturing eliminates the need for tooling, reduces material waste and enables more efficient production processes. These cost savings can have a profound impact on businesses by improving their competitiveness, enabling them to offer more affordable products and potentially reshoring manufacturing operations.

Moreover, additive manufacturing allows for greater design freedom and customisation. This opens up new business opportunities, especially in the realm of personalised products. Companies are increasingly using additive manufacturing to produce customised products, especially in the healthcare and sports industries. This capability not only enhances customer satisfaction, but also enables companies to differentiate themselves on the market. By leveraging additive manufacturing, businesses can tap into niche markets, create unique product offerings and establish themselves as innovators in their respective industries.

The disruptive potential of additive manufacturing is also evident in its impact on supply chains. Traditional manufacturing often relies on complex and lengthy supply chains, involving multiple suppliers and logistics operations. However, additive manufacturing can streamline the supply chain by enabling local production and on-demand manufacturing. This reduces lead times, eliminates the need for excess inventory and enables a more agile and responsive production system.

AM has the power to transform industries, challenge traditional business models and drive innovation. As the technology continues to advance and become more accessible, its impact on the economy and businesses is expected to grow significantly. According to available estimates, sales of 3D printed components and related services have been growing at an average rate of 25.6% over the last 34 years, with the market size of the AM industry passing the USD 18 billion (EUR 16.17 billion) mark in 2022 (Wohlers Associates, 2023). An increasing amount of materials are available with increasing properties, with the quality of some AM parts already matching or even surpassing the quality of parts produced by conventional methods.

While it is a rapidly evolving technology, it has already made significant advancements and gained widespread adoption in various industries. AM technology is widely applied in prototyping, speeding up product development, but is also used for industrial production of end-parts in aerospace, medical industries, power and energy, and some consumer markets (architecture, footwear, sport equipment, and eyewear). In addition, it still has a strong untapped potential in automotive, fashion, food and electronics. As the technology further expands to new materials, printing systems, and applications, it is expected to generate enormous growth opportunities throughout the manufacturing industry, which has a market size of $ 16.38 trillion (€ 14.72 trillion) (World Bank). Even if AM were to capture a low percentage share of this market, it could still amount to a revenue of hundreds of billions of US dollars.

1.3 Why this study?

Additive manufacturing has already demonstrated its transformative power by enabling the creation of complex geometries, reducing lead times and even customising products on-demand. From aerospace and automotive industries to healthcare and consumer goods, additive manufacturing has permeated a wide range of sectors, revolutionising traditional manufacturing processes. The continual emergence of new materials, enhanced printing techniques and innovative applications necessitates in-depth research to understand and harness the full potential of this technology.

AM has the potential to drive future economic growth and competitiveness. As countries and industries strive to establish themselves as leaders in the global market, staying at the forefront of technological advancements becomes paramount. Moreover, additive manufacturing can help address critical issues related to sustainability and environmental impact. As the world increasingly recognises the importance of sustainable practices, additive manufacturing offers the potential for reduced waste, optimised material usage, and localised production.

As additive manufacturing continues to shape the future of production, conducting comprehensive studies becomes an imperative step towards unlocking its full potential and reaping the benefits it offers across diverse sectors. This report, which covers a period until 2020, is a follow-on study and builds on the methodology developed in the first EPO study on patents and additive manufacturing (EPO, 2020). In contrast to the previous report, which considered only EP patent applications, the primary objective of this new study is to offer a comprehensive global perspective on AM innovation. Moreover, the new report places a stronger emphasis on the most important application domains: health and medical, and transportation, while also exploring various AM systems. The study provides valuable insights on the AM ecosystem that were derived from patent information and complemented with market and industry research, such as the latest Wohlers Report 2023. It will enable businesses and policymakers to make informed decisions and implement strategies that leverage AM technology effectively and to the highest benefit to society.

1.4 Outline of the study

Chapter 2 discusses the current state and expected development of the industry and sets out a methodology to study technology trends in AM based on patent data. Chapter 3 provides an overview of the main patenting trends in AM technologies over the last two decades. Chapter 4 focuses on the origin of AM innovation, while Chapter 5 presents the top patent applicants involved in AM. The study also contains case studies of three European high-growth technology companies innovating in AM technologies.

Box 1: 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. Once they lapse, the technical information in them becomes free for everyone to use. A patent can be maintained for a maximum of 20 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 (https://worldwide.espacenet.com/) contains more than 140 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. The legal status of the patent document can easily be checked within Espacenet.

2. The rise of additive manufacturing

2.1 Short history of AM

AM integrates various technologies, some of which have been in existence since the 1950s. These technologies include computer-aided design (CAD), computer-aided manufacturing (CAM), laser and electron energy beam technology, and computer numerical control (CNC) machining. By applying these technologies to a wide range of materials, a new industry emerged in the late 1980s with significant inventive activity, leading to an increase in patent applications.

The commercial adoption of AM began in 1987 when 3D systems introduced stereolithography (SLA), a process that utilises a laser to solidify thin layers of UV light-sensitive liquid polymer. SLA was developed by Chuck Hull, who is considered the pioneer of 3D printing and co-founder of 3D systems.[2] Chuck Hull's invention of SLA was a major breakthrough that laid the foundation for the development of 3D printing technology as we know it today. Over the past three decades, AM has experienced remarkable growth, transforming into a fully established industry.

Initially, AM was primarily used for prototyping purposes, but it has significantly evolved since then. Today, AM has expanded its applications to the production of end-products, showcasing its substantial growth potential in various sectors. With the capability to manufacture complex intermediate components and final products that were traditionally made by hand or through multiple manufacturing steps, AM has emerged as a disruptive force in manufacturing. Its ability to produce nearly any geometric shape has made it particularly well-suited for small-scale production of highly intricate components.

However, the transition from prototyping to end-product manufacturing requires continuous advancements in hardware, such as printers and printing methods, as well as the development of sophisticated and fast design, data analysis and print software. Additionally, the materials used in the printing process play a crucial role in enabling the production of functional and durable end-products. Ongoing research and development efforts are focused on enhancing these aspects of AM to unlock its full potential in end-product manufacturing. By addressing these challenges, AM can further revolutionise the manufacturing industry, enabling the efficient and cost-effective production of complex and customised components on a larger scale.

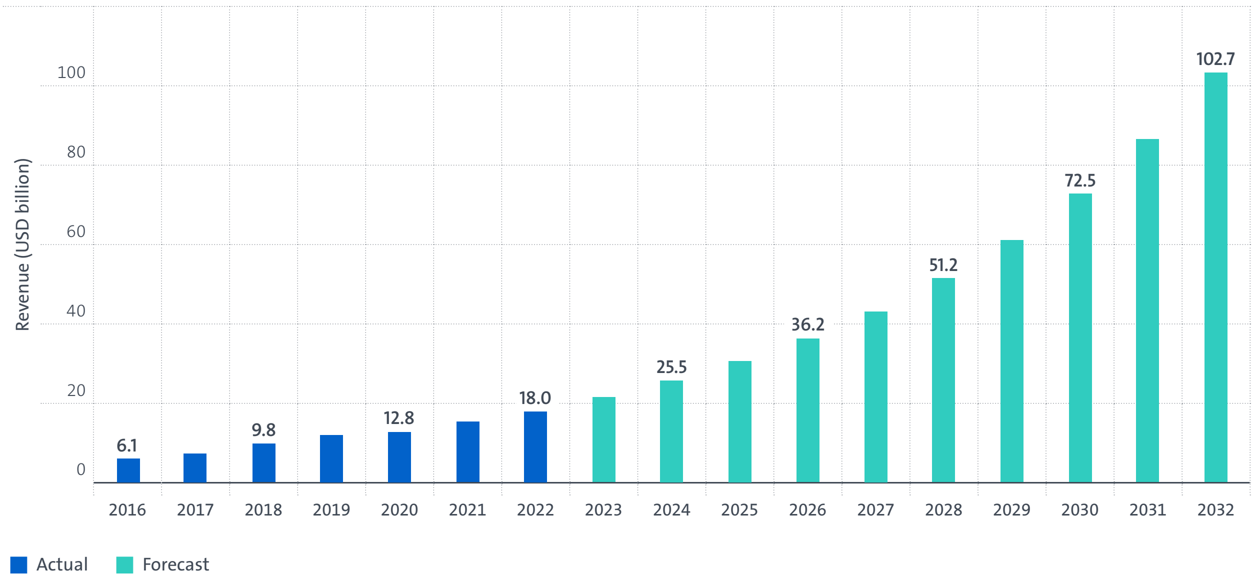
2 For his contributions to stereolithography, Charles Hull received the European Inventor Award 2014 in the category Non-European countries from the European Patent Office. See https://new.epo.org/en/news-events/european-inventor-award/meet-the-finalists/charles-w-hull

The market for additive manufacturing has experienced significant growth, as highlighted by data from the Wohlers Report 2023. In just six years, the industry revenue has tripled, soaring from approximately $6 billion in 2016 to $18 billion in 2022 (see Figure 1). This revenue includes all aspects of the AM market, encompassing AM systems, materials, software, lasers and AM services, such as parts production from independent service providers, system maintenance contracts, and consulting directly associated with AM processes. Despite facing challenges in 2021, the AM market showed resilience, with the volume of sold AM products and services growing by 18.3% in 2022. Interestingly, in the more recent period, AM services emerged as the most dynamic segment, representing $10.7 billion in 2022, outpacing AM products, which accounted for $7.3 billion in the same year. This can be interpreted as a sign of increased adoption of AM.

Looking ahead, numerous factors can influence the future trajectory of the AM market, including global economic conditions, political changes, and technological advancements. For example, the COVID-19 pandemic has had both positive and negative effects on the AM market. The overall economic slowdown during the pandemic affected several industries, leading to a decrease in demand for AM products and services. At the same time, the urgent need for medical equipment during the pandemic highlighted the agility and rapid production capabilities of additive manufacturing. Amid global transportation and logistics challenges, AM provided a way to locally produce goods, reducing dependency on international supply chains. Overall, experts anticipate that the remarkable pace of growth will persist in the next decade. Projections suggest that the AM market could surpass the $50 billion mark within the next five years, by 2028, and even exceed $100 billion by 2032.

Figure 1

Market size and forecast of AM products and services



2.2 The disruptive potential

The economic benefits of additive manufacturing are substantial and diverse. From cost savings through reduced tooling and inventory requirements to enhanced customisation, accelerated product development, and simplified maintenance, AM offers manufacturers a competitive edge.

One of the key advantages of AM is the freedom it provides to designers that is not possible with conventional manufacturing methods. AM can create nearly any 3D shape. By leveraging advanced design tools and techniques, such as generative design, designers can automatically generate multiple variations of a design based on specific inputs, such as material type and load requirements. This creative freedom allows for the optimisation of strength, stiffness, weight, manufacturability, and other parameters, resulting in parts that perform better or are less expensive than their conventionally manufactured counterparts.

AM also enables cost-efficient production of custom products, opening the door to mass customisation. This capability is particularly beneficial in sectors like healthcare, where individualised solutions for patients are crucial. By tailoring each part, such as a bone replacement or a hearing aid, to specific interests and needs, AM enhances consumer satisfaction and reduces the reliance on one-size-fits-all approaches.

AM also revolutionises inventory management. The consolidation of many parts into one through AM reduces inventory requirements, both on-site and in off-site warehouses. This consolidation, coupled with on-demand manufacturing, minimises the need for extensive storage, freeing up capital and providing companies with more flexibility to invest in other areas. Furthermore, reducing the number of parts in an assembly not only lowers manufacturing and production management costs but also decreases assembly time, labour, and transportation costs. AM's on-demand production capability is especially valuable for spare parts, where thousands of unique components can be required. Instead of maintaining costly inventories and facing logistical challenges, AM allows for the fabrication of spare parts as needed from digital inventory, eliminating physical storage and transportation bottlenecks. Digital files can be transmitted and printed on-site, reducing costs and ensuring timely availability.

Another significant economic benefit of AM is the elimination of tooling requirements. Unlike traditional manufacturing processes that heavily rely on moulds and fixed tooling, AM does not require these time-consuming and expensive components. This results in reduced production delays, as AM can quickly adapt to design changes and variations. Manufacturers can react more swiftly to changing market conditions, and production rates can be adjusted to match demand. This can also significantly reduce product development times and shortening time to market.

Moreover, AM technologies can contribute to environmental sustainability. By minimising material waste and utilising sustainable feedstock, such as recyclable and energy-efficient materials, AM reduces environmental impact. The ability to produce lightweight parts reduces energy consumption, and on-demand and local manufacturing further reduces transportation costs.

Box 2: 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, 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 rights (IPRs) 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. However, the majority of applications so far has addressed the hardware, i.e. the additive manufacturing machines and the processes for producing the products. 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.

2.3 AM adoption

Use cases

Additive manufacturing has found various applications in the manufacturing industry, as highlighted by recent surveys and studies. Prototyping continues to be the leading use case for AM, providing users with faster product development, lead times and greater design freedom. A survey by Hubs (Hubs, 2023) found that 66% of participants identified prototyping as their primary use of 3D printing, emphasising its role in accelerating the product development process. This aligns with Sculpteo's study (Sculpteo, 2022), which revealed that a quarter of their surveyed users utilise AM to speed up their product development by creating proof of concepts and prototypes. However, as users gain more experience with the technology, AM is also being recognised as a viable solution for tooling and end-use part production. Tooling applications enable users to enhance production lines and minimise machine downtimes, while end-use production, encompassing custom parts, low-batch production, and serial production, was cited in Hubs (2023) by 21% of respondents as their primary application and was mentioned as a goal of their AM activities by almost 50% of respondents in Sculpteo, 2022. According to research by Materialise, an AM company, a majority of businesses expect their use of 3D printing to remain consistent over the next five years, focusing on visual prototypes, personalised parts, and spare parts. With further advancements in AM technology and access to qualified experts, however, companies can leverage 3D printing to create new business opportunities and advance their manufacturing operations

Industries

The primary sectors driving the advancement and utilisation of this technology include aerospace, automotive and medical. The aerospace industry has been an early adopter of additive manufacturing, leveraging its benefits for low-volume production and design freedom. Aerospace OEMs have embraced 3D printing to produce lightweight components, improving aircraft fuel efficiency. Jet engines, structural aircraft parts, and interior cabin components are among the many parts manufactured using 3D printing technology in the aerospace sector. In the automotive industry, additive manufacturing has evolved significantly over the years. Various 3D printing processes are now employed for rapid prototyping, tooling, customisation, spare-part manufacturing, and even series production. Advancements in digitalised workflows and automation are enabling the exploration of 3D printing for serial mass production. The medical field has witnessed significant advancements in diagnostic and treatment solutions through additive manufacturing. Patient-specific implants, prosthetics, surgical guides and instruments, anatomical models, dental products and more are now being produced using 3D printing technology. Additive manufacturing allows for easy customisation based on a patient's medical scans, and it has the potential for point-of-care production, which allows manufacturing directly at the point where the products are needed for patient care.

However, several other industries are also exploring additive manufacturing and are ready for transformation (see Table 1 for different examples). Food printing, though still in its early stages, has shown promise in revolutionising the food industry. From printed pizzas and chocolates to meat substitutes and cultivated meat, 3D printing has the potential to reduce reliance on intensive animal farming. Custom nutrient profiles can be embedded in printed food to benefit medical patients or the elderly. The impact of 3D printing is also being felt in the fashion industry, particularly in footwear. Companies like Adidas have brought running shoes with 3D printed midsoles to the market, pushing the boundaries of innovation and customisation. AM could also make a significant impact in the construction sector, which is utilising AM to revolutionise building processes, enabling the creation of complex architectural designs and reducing material waste. With 3D printing technology, it is possible to construct customised structures, prefabricated building components, and even entire houses. This innovative approach allows for faster construction times, cost savings, and enhanced design possibilities.

Table 1

Use cases of AM technology for the production of final parts by industry

Aerospace	– Metal fuel nozzles – Plastic brackets, clips – Integrated hydraulic systems, actuators – Pipe elbows for fuel systems – (Turbine) blades – In-cabin separation walls – 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
Health and medical	– Titanium-alloy orthopaedic devices (hip implants) – Implants for facial and skull disorders – Copings for crowns and bridges – Hearing aids
Consumer goods	– Midsoles – Heels – Insoles – Ski boots – Head protection
Automotive	– Body shell parts – Chassis joints – Ventilation systems – Brake cooling ducts – Pedal spacers
Food	– Meat – Customised chocolates
Construction	– Customised facades – 3D printed buildings and bridges – Architectural models

Geography

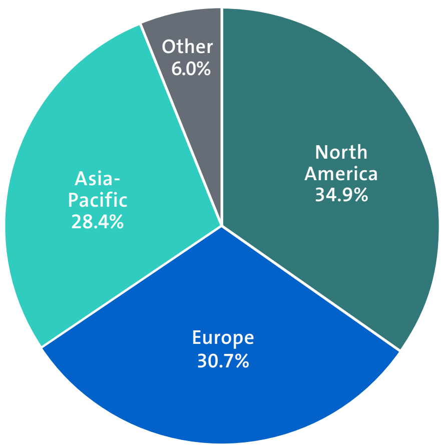
AM adoption varies also across different regions. Research by Wohlers (Wohlers Associates, 2023) indicates that approximately 34.9% of all industrial AM systems installed worldwide are located in North America (see Figure 2). Europe follows closely, with 30.7% of industrial systems installed, while the Asia-Pacific region accounts for 28.4% of installations. The remaining 6% of systems are distributed across Central America, South America, the Middle East, and Africa. Interestingly, if compared to 2019 (Wohlers Associates, 2019), North America and Asia-Pacific regions' shares declined by a few percentage points, while the shares of AM systems installed in Europe and other regions increased over the same period.

On the country level, the US maintains its dominance on the AM market, accounting for 33% of the total installations. P.R. China, with 10% of installations, holds the second-largest installation base, followed by Germany at 8.5% and Japan at 8.2%. In Europe, Italy (4.7%), UK (3.5%) and France (3.4%) also have notable shares.

These statistics highlight the concentration of AM systems in certain regions, with the US taking the lead in terms of installed machines. However, the Asia-Pacific region and Europe also demonstrate significant adoption and are home to substantial numbers of industrial AM systems. As the technology continues to advance and adoption increases globally, it will be interesting to observe how these regional trends evolve and how other countries and regions contribute to the growing AM market.

Figure 2

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



2.4 Adoption and innovation challenges

AM is already the standard technology for prototyping and product development. However, it also holds enormous potential for end-use part production. Several innovation challenges are being addressed for its widespread adoption.

For AM to become a common method of end-use part production, systems need to become significantly faster, which will help reduce the production cost per part. The build time of AM processes is a major contributor to part cost and its reduction will improve break-even points from hundreds or thousands of parts to tens or hundreds of thousands, making it more attractive for the industry. AM systems also need to increase machine throughput to drive adoption. This can be achieved not only through faster operating speeds, but can also be achieved with larger built volumes, optimised part packing, and automated part removal processes. For example, continuous production techniques, such as using a conveyor belt, can improve throughput and enable the production of extremely long parts (Wohlers Associates, 2023).

The concept of replacing inventories with a digital version, combined with on-demand manufacturing, holds great potential. However, the adoption of this approach has been weak thus far. Overcoming barriers related to supply chain integration of AM processes, their standardisation, and logistics around them is necessary to successfully integrate AM machines into existing production workflows.

The cost of industrial AM machines and materials remains significant. Both machines and materials are getting cheaper, but remain relatively expensive, especially when compared to conventional manufacturing methods. In particular, material costs impact manufacturing costs when part volumes increase. Also, AM equipment often relies on vendor-specific material and control software, with limited integration between different machines or with wider plant production-control systems. Obtaining consistent quality and stable productivity can be challenging due to the technology and know-how required, too.

The effort and cost involved in pre- and post-processing of AM are often underestimated. Post-processing of AM parts, including the removal of support structures and finishing operations, can account for a significant part of the total cost of an AM part. Additionally, upfront labour, especially for low-volume manufacturing, can be expensive, affecting the overall cost-effectiveness of AM.

Qualification and certification processes associated with AM poses another obstacle to its widespread adoption. The industry requires adherence to specific standards and regulations to ensure part quality, safety, and compliance. Therefore, the development of international standards on the application of AM technologies in different industry sectors will likely have a significant impact on the uptake of AM technologies.[3]

However, the main non-technical obstacle to AM adoption is that manufacturers struggle to understand how AM can benefit them. Design engineers often lack knowledge of the capabilities of AM systems and how to design for AM effectively. The true benefits emerge when designers exploit the unique capabilities of AM, such as combining multiple features into a single component, reducing the overall number of parts, or eliminating subsequent fabrication steps, and not by just changing an existing component from conventional manufacturing to AM (see McKinsey, 2022). According to a recent survey, the two main challenges to adoption of AM are difficulty to recruit an expert workforce and the lack of experience and knowledge inside the company, even before the speed and cost considerations (Materialise, 2023).

The AM market is still in a developing phase and remains highly R&D-intensive. Many AM system manufacturers are spending over 30% of their annual revenue on R&D (Wohlers Associates, 2023). While AM will not replace conventional manufacturing entirely, it is seen as a complementary technology. It is well suited for producing difficult, expensive or customised parts, but conventional manufacturing is more efficient for other components. The cost of AM parts is expected to decline in the future, but it may remain more expensive for high quantities or low-value products with simple shapes. Additionally, the complexity of AM parts requires significant time investment by designers, and producing high-quality parts demands talent, effort and expertise. It is also unlikely that AM will make widespread adoption in

3 According to the website of the technical committee on additive manufacturing ISO/TC 261 of the International Organization on Standardization, there are 27 published standards and there are 32 standards under development at the time that this report is published (see https://committee.iso.org/home/tc261).

private homes, since operation of AM machines requires specialised training and knowledge, and requires ongoing maintenance. However, it is beyond doubt that AM has the potential to revolutionise the way products are designed, manufactured and distributed. Its impact will be significant, shaping the future of manufacturing across various sectors and unlocking new possibilities for innovation, customisation, sustainability, and supply chain resilience.

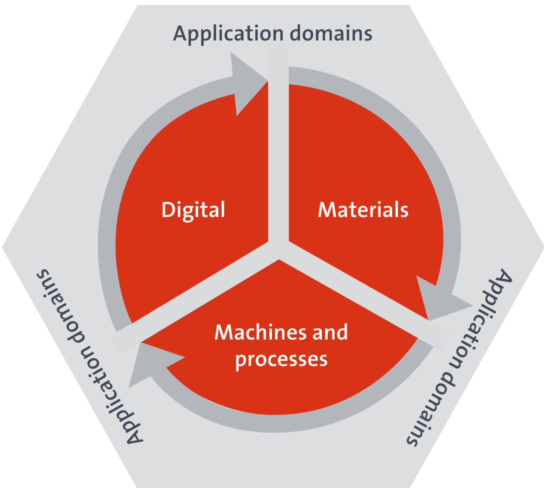
2.5 Cartography of additive manufacturing technologies

AM is a technology that spans different disciplines, incorporating a wide range of technical expertise. At its core, it is a digital manufacturing process that begins with a digital representation of the desired product. This involves working with digital files and instructing machines to operate in a manner that transforms the design into a physical object. The choice of material is crucial, as it must possess the necessary structure and properties suitable for the specific product application. Considering the intricate nature of AM, all the technologies that contribute to these aspects are taken into account when mapping out the landscape of AM technologies.[4]

The AM cartography, which is presented in Figure 3 and builds upon the methodology developed in the previous EPO study on patents and additive manufacturing (EPO, 2020), comprise four technology building blocks. The building blocks *Machines and processes, Materials*, and the *Digital* infrastructure together enable additive manufacturing. The fourth building block Application domains contains all inventions that are pertinent to the specific application field depending on the industry where it is used. It is a transversal category covering the applications of AM technologies and denotes the main field of use of the manufactured product.

Figure 3

Illustration of the four additive manufacturing technology sectors



Source: EPO

4 Screen printing (seriography) has not been considered part of additive manufacturing. Although the technique has been 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.

2.5.1 Machines and processes

Machines and processes refers largely to printers that bring the digital design to reality, the energy source used to shape or solidify the material, but also to other peripheral devices that have been developed for the different AM techniques. In general, it covers all AM techniques described in the ISO/ASTM52900:2021 standard, namely binder jetting, directed energy deposition, fused filament fabrication, material jetting, powder bed fusion, sheet lamination and vat photopolymerisation. Almost all of the commercially available AM systems fit into one of these categories. According to the standard, each AM process can differ in several aspects:

— *Material and material form*: This criterion refers to the type of materials and their physical state used in the AM process, i.e. nature of the feedstock. It differentiates for example between powder-based processes (binder jetting, powder bed fusion), filament-based processes (fused filament fabrication), liquid-based processes (material jetting, vat photopolymerisation) and sheet-based processes (sheet lamination).

— *Energy source*: This criterion focuses on the type of energy used to shape or solidify the material. Typical energy sources are lasers, electron beams, ultrasound, LED or IR lamps. Depending on the technique and the material, one or several energy sources are used for the consolidation of the material.

— *Layering approach*: This criterion refers to the method by which the material is deposited and built up layer by layer. It differentiates between processes that use a powder bed and selectively bind or fuse the powder (binder jetting, powder bed fusion), processes that extrude or deposit material in a continuous path (fused filament fabrication, material jetting, directed energy deposition), and processes that bond and stack sheets of material (sheet lamination).

— *Support structure*: This criterion addresses the need for support structures during the printing process to provide stability or anchor overhanging features. It differentiates between processes that use sacrificial materials (such as soluble supports in material jetting or vat photopolymerisation) and processes that require additional structures or supports (such as binder jetting, powder bed fusion and fused filament fabrication).

More detailed aspects related to integral components such as laser optics, electron beam design and extruder heads, have been considered as well.

AM process categories explained:[5]

— *Binder jetting*: this technique involves depositing a liquid binding agent onto a powdered material bed to selectively bind the particles and create a solid object

— *Directed energy deposition*: uses focused thermal energy sources, such as lasers or electron beams, to melt and fuse materials while they are deposited layer by layer

— *Fused filament fabrication (or material extrusion)*: melts and extrudes a filament, which is selectively dispensed through a nozzle

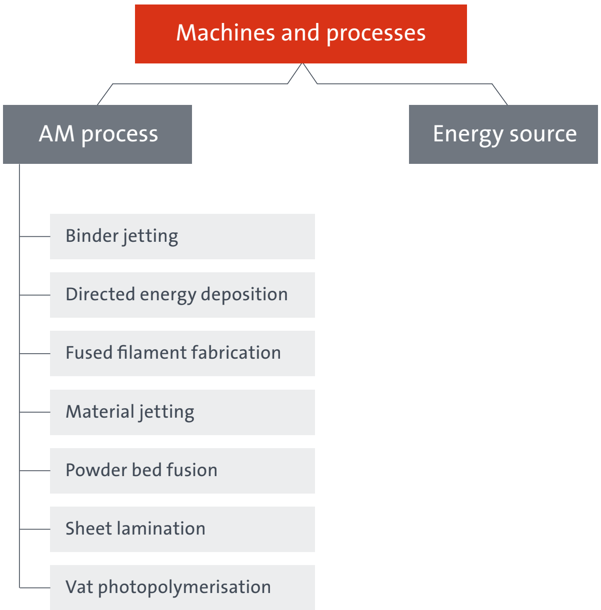
— *Material jetting*: involves selectively jetting droplets of feedstock material, which are then solidified layer by layer

— *Powder bed fusion*: uses a thermal high-energy source, such as a laser or electron beam, to selectively melt and fuse regions of a powder bed

— *Sheet lamination*: involves layering and bonding sheets of material together to form a part

— *Vat photopolymerisation*: uses a vat of liquid photopolymer resin and a light source to selectively cure and solidify the resin layer by layer

5 See ISO/ASTM 52900:2021 for exact definitions of the AM process categories.

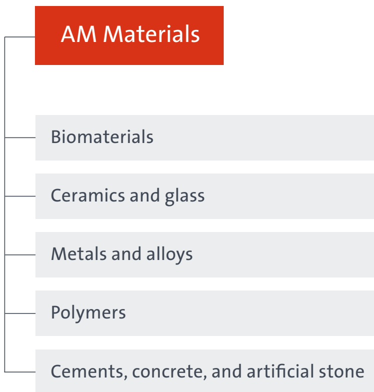


2.5.2 Materials

Materials are the input for the AM process and utilised to create objects and structures. They can vary depending on the specific additive manufacturing process, desired properties of the final object and application requirements. They are often produced as solids, in powder form, in wire or sheet feedstock, or as a liquid or slurry, and may differ in their mechanical, thermal, chemical, optical or electrical properties, dependent on the specific application and requirements.

Materials include core materials, but also assisting and support materials. Core materials, also known as build materials or primary materials, are the main materials used to create the desired object or structure through additive manufacturing. These materials form the bulk of the printed part and provide its primary characteristics, such as strength, durability and functionality. For example, in fused filament fabrication (FFF), the core material is typically a thermoplastic filament melted and extruded layer by layer to build the object. In powder bed fusion (PBF), metal or polymer powders serve as the core material, which is selectively fused together using heat or a laser. Support structures or support materials are temporary structures used to provide stability and prevent deformation or collapse during the printing process. These structures are necessary when printing objects with overhangs, complex geometries or intricate features that would otherwise be unsupported during the building process. Assisting materials often have different properties from the core material, such as being water-soluble or breakable. The specific assisting material used depends on the AM technique and the core material being printed. For example, in material jetting, support structures are typically printed using a different material that can be easily removed manually or dissolved in a solvent. In powder bed fusion processes, such as selective laser sintering of polymers, the surrounding unconsolidated powder in the bed can act as a self-supporting material during printing.

It is worth noting that the materials used in additive manufacturing continue to expand as research and development efforts advance, enabling the use of new materials with unique properties and capabilities. However, this cartography distinguishes between the five currently most common types of materials used in AM: *polymers, metals and alloys, ceramics and glass, cements, concrete and artificial stones, and biomaterials.*[6]



6 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.

— *Polymers*[7]: Various types of polymers and plastics are widely used in AM. These include acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polyamide (nylon), polyethylene terephthalate (PET), polypropylene (PP) and many others. Polymer-based materials are often used in filament-based processes like fused filament fabrication (FFF). This category comprises both the synthesis and the modification of compositions. In addition, the production and modification of artificial fibres or textiles is also included. Photo-sensitive materials were also considered.

— *Metals and alloys*[8]: Additive manufacturing techniques such as powder bed fusion (PBF), directed energy deposition (DED) and binder jetting (BJ) can work with metals. Common metal materials include stainless steel, aluminium, titanium, nickel alloys, cobalt-chrome alloys and precious metals like gold and silver. This field covers 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*[9]: Comprise oxides, non-oxides as well as the ceramic-based composites. Ceramics are used in AM for applications requiring high-temperature resistance, chemical inertness, or specific electrical properties. Materials like alumina, zirconia, silica and hydroxyapatite (used in biomedical applications) are commonly used in ceramic-based additive manufacturing processes. Glass compositions were also included.

— *Biomaterials*[10] : Additive manufacturing plays a significant role in biomedical applications, where biocompatible and bioresorbable materials are used to create implants, tissue scaffolds, and medical devices. This field includes only materials for the soft tissues and scaffolding, i.e. (living) cell cultures, polypeptides and polysaccharides.

— Compositions of *cements*[11], concrete or artificial stone are the basis for the last subcategory.

7 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.

8 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 to tailor the properties of the final AM parts to specific product requirements.

9 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 (ZrO_2), which is used for making teeth, crowns and other tailor-made dental objects. Alternatively, alumina (Al_2O_3) 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.

10 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/medical*.

11 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 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.

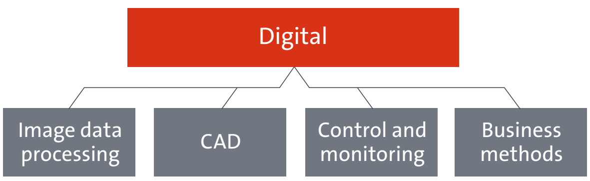
2.5.3 Digital

Additive manufacturing relies heavily on digital aspects throughout the entire process, from design to production. It comprises not only the digitalised design of the product to be manufactured, but also the monitoring and control of the printing process and the printing machine.

Any process of additive manufacturing starts from a digital representation of a product. Computer-aided design (CAD) software is used to create or import digital 3D models of objects to be printed. Designers and engineers utilise CAD tools to define the geometry, dimensions and other specifications of the desired part. These digital models serve as the foundation for the entire additive manufacturing process.

The digital design is then transformed into a build volume, sliced into layers. Slicing software takes the digital 3D model and converts it into a set of instructions that the 3D printer can understand. This process involves slicing the model into thin horizontal layers and generating toolpaths, which determine the movement and deposition of material for each layer. Slicing software also allows for adjusting parameters like layer thickness, infill density, support structures and print speed.

While the object is being manufactured, the printing process can be monitored and controlled. The machine control software operates the 3D printer. It interprets the sliced data and coordinates the movements of the print head or platform. This software controls critical parameters such as deposition speed and the positioning of the print head. It ensures precise and accurate material deposition based on the instructions derived from the digital model. The process control is particularly important for high-end products requiring certification.

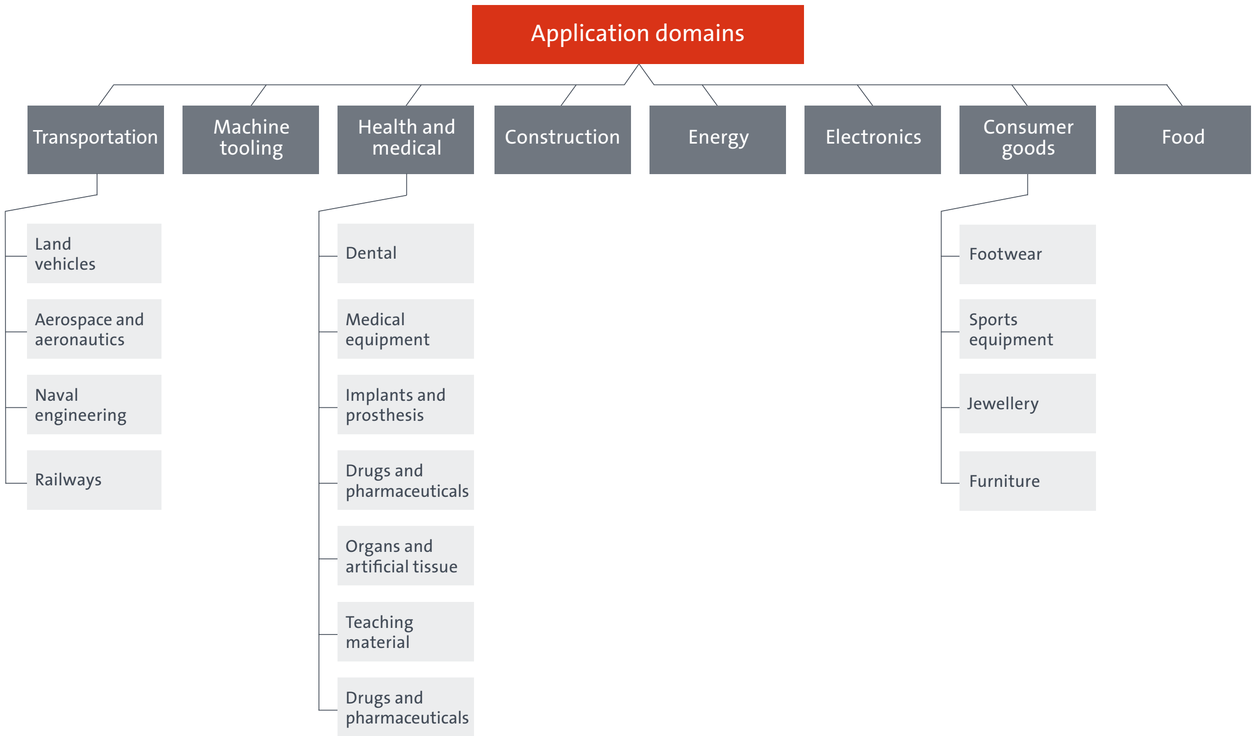


Another aspect of the digital character of AM is the possibility to manufacture remote from the place of design. Also, several digital services related to the AM process are emerging as the technology continues to advance. Additive manufacturing enables on-demand production and decentralised or even remote manufacturing, where parts can be printed through contractual agreements. Digital aspects come into play in managing digital inventories, where digital models of parts can be stored, organised and accessed when needed. Digital distribution platforms are also emerging that facilitate the sharing, selling and downloading of 3D printable designs, enabling a global network of digital manufacturing capabilities. As a result, cyber protection also becomes essential for safeguarding data files used for design and manufacturing instructions. All these aspects are also encompassed within the realm of AM's digital landscape.

2.5.4 Application domains

Over time, the use cases and application areas for AM have experienced a remarkable evolution, driven by technological advancements and expanding possibilities. Initially, AM was primarily used for rapid prototyping, enabling engineers to quickly validate and iterate designs. However, its potential soon extended far beyond prototyping, leading to a broadening range of applications. As AM technologies matured and materials improved, industries began to embrace AM for end-use production. It found its place in sectors such as aerospace, automotive and medical, where complex geometries, lightweight structures and customisation were highly valued. The medical field witnessed significant advancements through AM, with personalised implants, prosthetics and surgical guides becoming a reality. AM's impact spread to the consumer market as well. From customised jewellery and fashion accessories to home decor and artistic creations, AM turns design concepts into physical objects with ease. As AM technology continued to advance, new materials and multi-material capabilities expanded the range of applications even further. Functional prototypes, electronics, embedded sensors and even food and bioprinting became areas of exploration. The evolution of AM continues with advancements in materials, process speed, scalability and digital integration and other industries, like construction, electronics and energy are embracing the potential of additive manufacturing. AM's ability to integrate multiple materials and functionalities into a single part will open doors to innovative designs and novel applications in more industries.

To reflect these possibilities, but also taking the latest developments and current limitations into consideration, eight different application domains have been identified: *transportation, machine tooling, health and medical, food, energy, electronics, consumer goods and construction.*



1. *Transportation:* In aerospace and aeronautics, AM is utilised to produce lightweight, complex geometries that were previously unachievable. Aircraft engine components, such as fuel nozzles, turbine blades, and brackets, are being 3D printed using high-performance materials, resulting in enhanced fuel efficiency and reduced emissions. In the automotive industry, AM is employed for prototyping, tooling and production of end-use parts. This includes interior components, customised vehicle accessories, and even structural elements like chassis and brackets. AM enables design optimisation, weight reduction and functional integration, leading to improved performance and energy efficiency. Additionally, AM finds applications in the railway sector for producing lightweight and durable components, such as train interiors, seat structures and even custom spare parts. In the naval sector, AM is utilised for applications such as prototyping of complex ship components, rapid production of spare parts and even the creation of lightweight, custom-designed naval structures.

2. *Machine tooling:* AM is increasingly finding applications in machine and industrial tooling. It is being used to create complex and lightweight tooling components, such as jigs, fixtures and moulds, which can be customised for specific manufacturing needs, reducing lead times and costs. AM enables the production of intricate internal cooling channels, conformal cooling and optimised tool geometries enhancing tool performance and efficiency.

3. *Health and medical:* AM has made significant strides in the health and medical sector, revolutionising patient care and advancing medical technologies. Customised implants, such as cranial and orthopaedic implants, are now produced with precise patient-specific geometries, enhancing fit and functionality. Additive manufacturing enables the production of complex anatomical models that aid in surgical planning and education. In the field of prosthetics, AM allows for personalised and lightweight designs, improving comfort and mobility for individuals. Moreover, bioprinting techniques have shown promise in tissue engineering, with the ability to create artificial organs, skin grafts and even functional blood vessels. Additionally, AM plays a vital role in creating patient-specific surgical instruments and guides, ensuring accuracy and efficiency during procedures.

4. *Construction:* Additive construction is developing as an AM application field. A notable application is the 3D printing of architectural structures, where large-scale printers deposit concrete or other construction materials layer by layer, enabling the creation of complex geometries and customised designs. Additionally, AM is being used to fabricate prefabricated components and building modules, streamlining construction timelines and reducing waste.

5. *Energy:* Applications range from prototyping to end-use parts. One prominent application is in the production of complex geometries for gas turbine components, enabling enhanced efficiency and performance. Additionally, AM is being utilised for the manufacturing of customised parts for renewable energy systems, such as wind turbine blades and solar panels, enabling improved energy capture and optimisation. Furthermore, the energy sector is exploring AM for the production of lightweight structures and heat exchangers, contributing to reduced weight and increased energy efficiency in various energy systems.

6. *Electronics:* AM enables the production of complex, lightweight and miniaturised components such as antennas, connectors and sensor housings with intricate geometries that are challenging to achieve using traditional manufacturing methods. Additionally, additive manufacturing allows for the integration of circuits, conductive traces and even embedded sensors directly into 3D-printed parts, enabling the development of innovative electronic devices and smart objects.

7. *Consumer goods:* AM has found widespread applications in the consumer goods sector, revolutionising industries such as footwear, sports equipment, jewellery, furniture and more. In the footwear industry, AM enables the production of custom-fit shoes with intricate designs and optimised performance. Sports equipment manufacturers leverage AM to create lightweight and highly customisable products, such as personalised bike helmets and tennis racquets. In the realm of jewellery, AM allows for intricate and unique designs, empowering artisans to bring their creative visions to life.

8. *Food:* AM is utilised to create intricate and customised food designs, such as chocolate sculptures, cake decorations and confectionery with complex geometries. Additionally, 3D printing technology is enabling the development of personalised nutrition, where tailored food products, such as nutrient-rich snacks or dietary supplements, can be produced to meet individual dietary needs and preferences.

Box 3: Patent metrics

The identification of patent applications related to the various parts of the AM cartography was carried out using knowledge of EPO expert examiners, 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 across all technologies and collected through a network of AM technology specialists within the EPO.

Published international patent families (IPFs) are used in the study as a uniform metric to measure patenting activities in the different categories of AM technologies. Each IPF identified as relevant for AM technologies is assigned to one or more technology sectors, or fields of the cartography, depending on the technical features of the invention.

Each IPF covers a unique invention and includes patent applications targeting at least two countries. More specifically, an IPF is a set of applications for the same invention that includes a published international patent application, a published patent application at a regional patent office or published patent applications at two or more national patent offices.[12] It is a reliable proxy for inventive activity because it provides a degree of control for patent quality by only representing inventions for which the inventor considers the value sufficient to seek protection internationally.

The reference year used for all statistics in this report is the earliest publication year of each IPF, which usually is 18 months after the first application within the patent family.

The dataset was further enriched with information about the applicants of the IPFs. In particular, data was retrieved from Bureau van Dijk's ORBIS database, Crunchbase and other internet sources, which was used to harmonise and consolidate applicant names and identify their type.

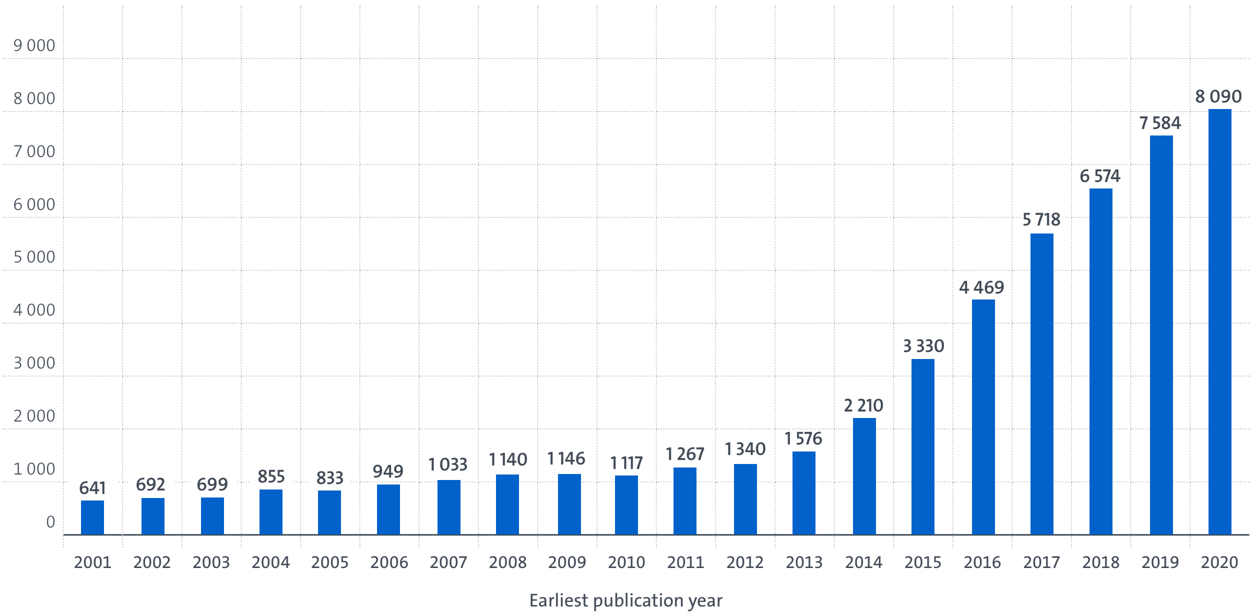
12 The regional patent offices are the African Intellectual Property Organization (OAPI), the African Regional Intellectual Property Organization (ARIPO), the Eurasian Patent Organization (EAPO), the European Patent Office (EPO) and the Patent Office of the Cooperation Council for the Arab States of the Gulf (GCCPO).

3. Patenting trends in additive manufacturing technologies

3.1 General trends

Figure 4

Trends in IPFs in all additive manufacturing technologies, 2001-2020

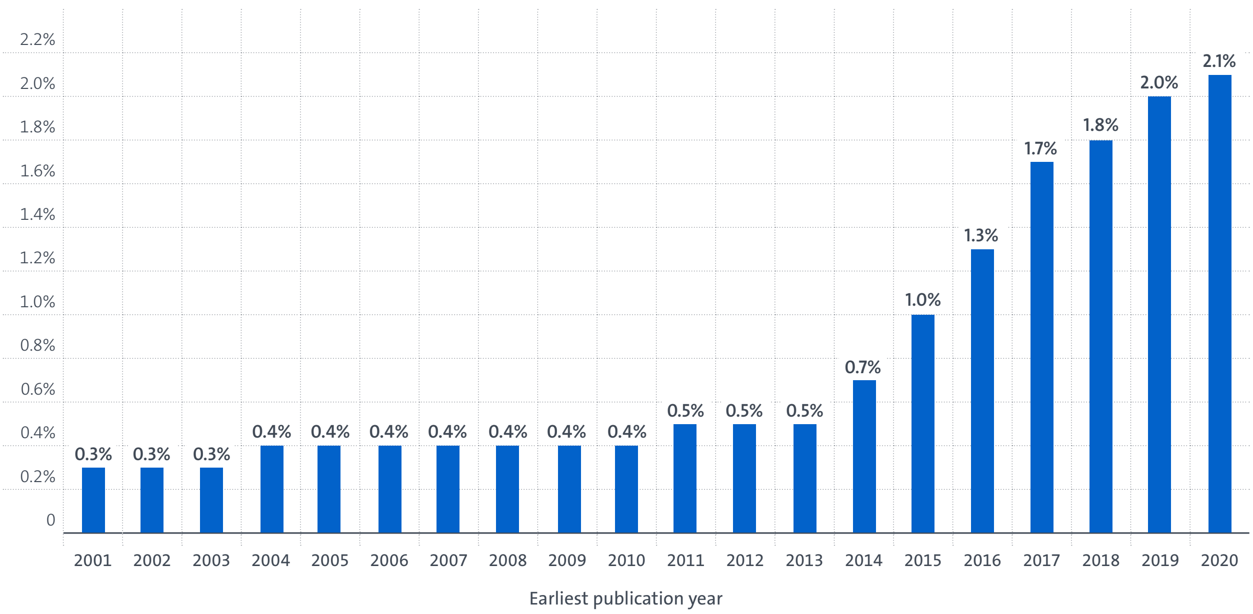


Source: EPO

As the field of AM continues to evolve, patent data provides valuable insights into the technological landscape and areas of innovation within the industry. The trends in patenting in AM that are presented in Figure 4 reveal significant growth and a rising prominence in the field. Between 2001 and 2020, an impressive total of over 51 000 inventions were subject to IPFs related to AM. Notably, the number of IPFs in AM has been consistently increasing since the early 2000s. While the annual IPF count merely doubled between 2001 and 2012, it experienced an exceptional five-fold increase from 2013 to 2020. The number of IPFs surged from 1 576 in 2013 to over 8 000 in 2020, showcasing a remarkable growth trajectory. Moreover, during this later period, AM technologies witnessed significantly faster growth in IPFs compared to overall patenting activity across all technology fields. The share of AM international patent families out of the total IPFs escalated from less than 0.5% before 2013 to surpass 2% by 2020, indicating a growing significance and interest in protecting AM innovation (see Figure 5).

Figure 5

Share of AM IPFs in all technologies, 2001–2020

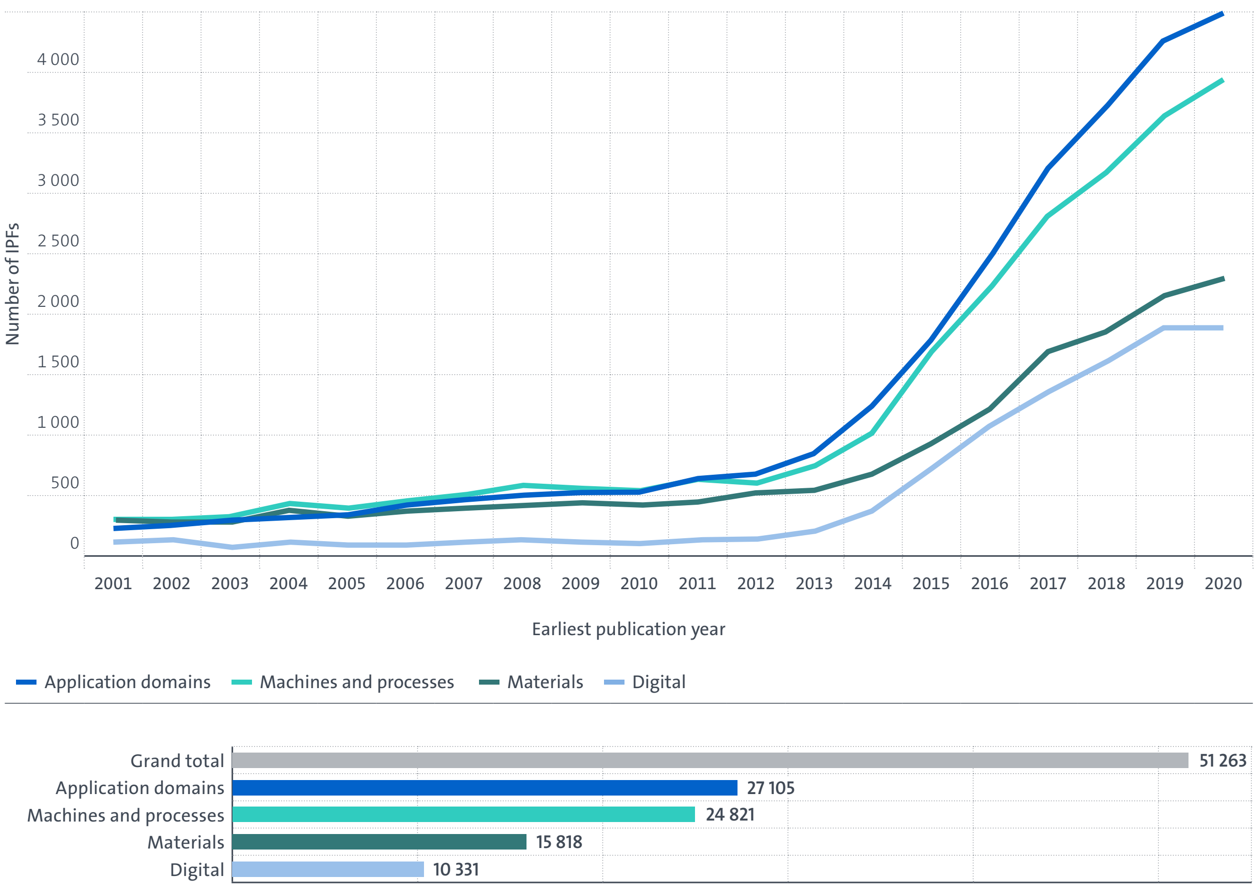


Source: EPO

The two largest AM technology sectors based on the number of IPFs are the application domains, and machines and processes (see Figure 6). Between 2013 and 2020, both sectors exhibited remarkable growth, with a compound annual growth rate (CAGR) close to 27% (see Figure 7). These sectors have been at the forefront of innovation, driving advancements in diverse applications and the development of efficient AM machines and processes. The materials sector is the third largest in terms of IPFs. With over 15 000 IPFs recorded since 2002, the materials sector has been instrumental in expanding the range of materials available for AM. However, its growth rate has been comparatively lower than the other sectors during the specified period, with a CAGR of 23%. On the other hand, the digital sector, although the smallest among the four technology sectors, demonstrated the strongest growth since 2013, with a CAGR of 37%. The digital sector encompasses technologies related to software, data processing, and digital design tools that enable and enhance the AM printing process. While the growth rate has slowed down in more recent years, it still retains considerable momentum and continues to contribute to the overall advancement of AM technologies.

Figure 6

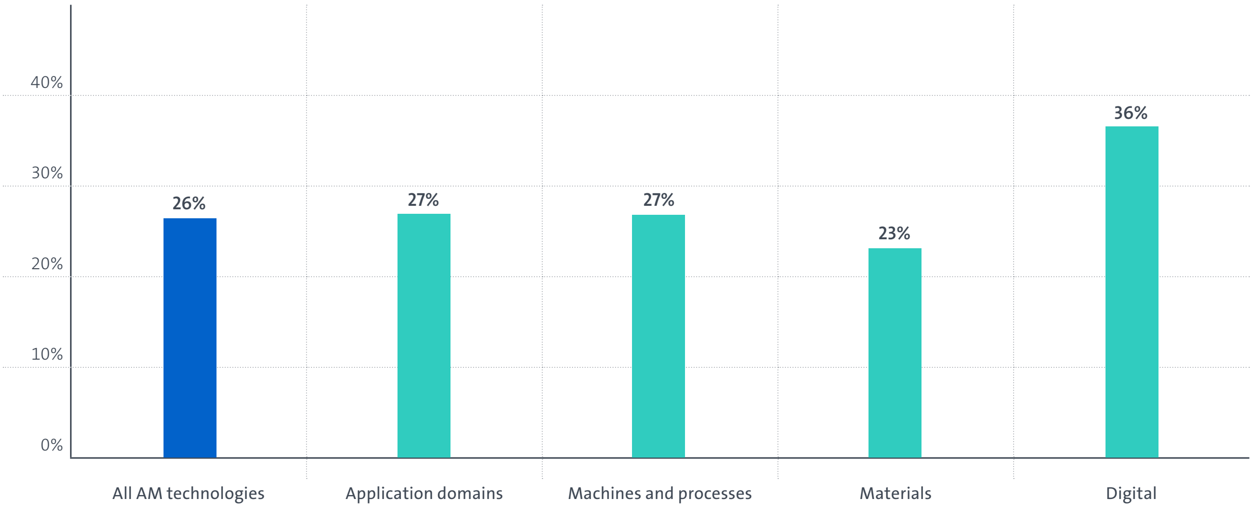
Trends in IPFs in AM technology sectors, 2001–2020



Source: EPO

Figure 7

CAGR in AM technology sectors, 2013–2020



Source: EPO

3.2 Trends in AM technology sectors

This section presents the patenting trends within each of the four technology sectors of additive manufacturing in the period 2001 to 2020.

In terms of materials, polymers emerged as the largest field, accumulating over 8 500 IPFs throughout the entire period (see Figure 8). The pace of developments started to accelerate in 2013, as the number of IPFs per year surged from around 300 to nearly 1 100 in 2020. Indeed, polymers have always been the major area of AM materials.

Polymers, be it as powder, photopolymers or filaments, is the largest materials market segment. There is a wide and expanding range of polymer options available, although the selection is still relatively smaller compared to conventional manufacturing methods. Polymer materials for AM can be chosen based on various factors such as tensile strength, rigidity, biocompatibility or colour. They are classified into two groups based on their behaviour at high temperatures. Thermoplastics are a type of polymer that becomes pliable when heated and solidifies upon cooling. They can be melted and re-melted multiple times without significant degradation. Thermoplastic filaments are widely used in fused filament fabrication (FFF) or material extrusion-based additive manufacturing processes. Photopolymers are light-sensitive polymers that undergo a chemical reaction, such as curing or solidification, when exposed to specific wavelengths of light, typically ultraviolet (UV) light. They are commonly used in vat photopolymerisation-based additive manufacturing techniques. AM polymers still tend to be more expensive compared to equivalent materials used in conventional manufacturing due to several factors. The production of feedstock for AM is typically carried out in low volumes, which increases costs compared to mass-produced conventional plastics. Additionally, the processing of polymers for AM is more involved compared to conventional plastics processing. Notably, prices for additive manufacturing feedstock have remained relatively stable for over two decades, due to low competition from third-party material suppliers. Recently, there is a growing interest in developing more sustainable polymers with improved chemical resistance and advanced mechanical properties for additive manufacturing, reflecting the industry's focus on creating more durable and high-performance parts.

Biomaterials boast over 3 600 IPFs and represent an active and rapidly evolving field, with continuous advancements aimed at improving biocompatibility, functionality and customisation. Even before 2013 it was the second largest field according to the number of IPFs. Biomaterials can be used in a range of medical applications, such as in tissue/organ repair, drug delivery, clinical medicine, tissue engineering and prosthetic implants specifically designed for the patient. Nevertheless, while some materials are more mature in terms of technological readiness, others are still in an exploratory phase. Advanced biomaterials, like tissue-specific scaffolds, bio-printable hydrogels and bioactive ceramics, are still in the developmental stage and has been slow to transition to the commercial sector. They often require further research and optimisation to reach widespread implementation. Bio-inks composed of living cell cultures enable the direct printing of cells, allowing for the creation of complex 3D structures with cellular functionality with the goal to fabricate functional tissues for organ transplantation and tissue engineering. Researchers are still exploring various techniques and formulations to enhance cell viability, improve printing resolution, and optimise bio-ink's mechanical and biological properties. Polypeptides and polysaccharides are also gaining attention as biomaterials for AM, since they offer unique characteristics such as biocompatibility, biodegradability and the ability to regulate cellular responses. Ongoing advancements in materials science, bioprinting techniques and tissue engineering approaches are driving the field forward, and patents support collaborations between academia, industry and medical professionals for translating these technologies into practical applications.

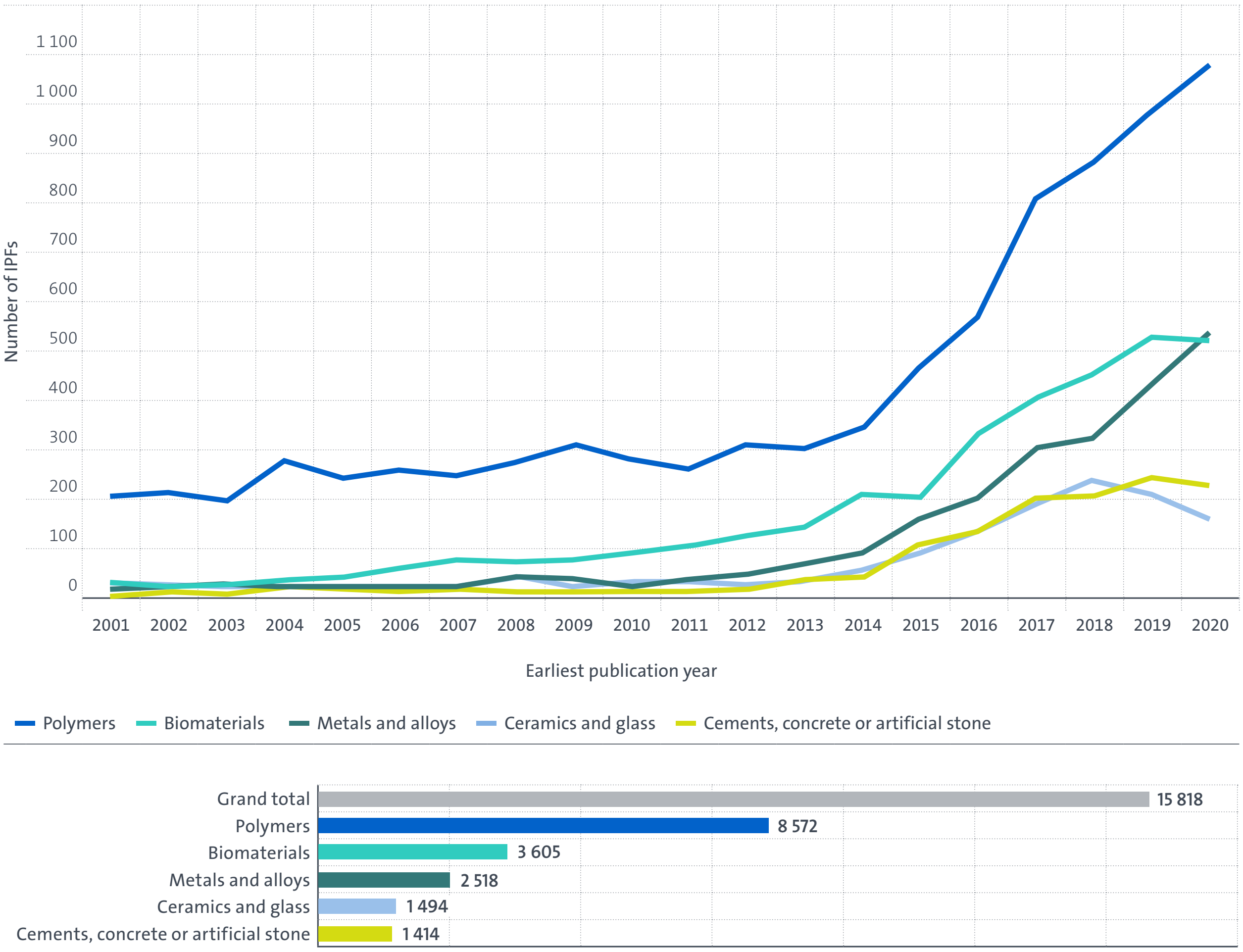
Although smaller in size, the market for AM metal applications has been growing even faster than the market for AM polymers and innovation has followed suit. Metals and alloys experienced very rapid growth in the past decade, reaching over 2 500 IPFs overall, catching up to biomaterials with 538 IPFs in 2020 alone. The range of metals and alloys, such as steels, titanium, nickel, cobalt, aluminium, copper or gold, is continuing to grow for AM. The market for metal powder and alloys in AM is the second largest after polymers and experiencing significant growth and intensifying competition. After an increase from 3 000 tons to 5 600 tons between 2019 and 2021, AM consultancy Ampower[13] predicts a more than 30% annual sales increase over the next four years, with metal 3D printing powder demand expected to rise to 22 456 tons in 2026. As the number of powder manufacturers is rising, the sector is becoming more competitive. Since metal powders are increasingly becoming a commodity that can be obtained from many manufacturers in a very good quality, falling prices have been observed in some materials, which will further drive the expansion of AM printing in this area. Special alloys and materials development remain areas of focus for further innovation and market growth. For example, refractory metals, known for their high structural integrity at elevated temperatures, are of particular interest for hypersonic applications. Powder-based AM processes offer an attractive alternative to conventional manufacturing, expanding the design possibilities for refractory metal parts. Additionally, the emergence of powder recycling is another significant recent advancement in metal AM, contributing to sustainability and cost-effectiveness in the industry.

On the other hand, ceramics and glass, as well as cements, concrete or artificial stone, represented the smallest material fields, each with less than 1 500 IPFs. Notably, both fields appeared to have reached a saturation point following strong growth between 2013 and 2018. Ceramic and glass materials are offered by a growing number of companies. Ceramic powders or glass filaments are used as feedstock in various industries such as aerospace, automotive, biomedical and electronics due to ceramics' desirable properties like high temperature resistance, wear resistance and chemical stability. Glass 3D printing, on the other hand, enables intricate glass structures to be fabricated with high transparency and unique optical properties. Recent developments are exploring new ceramic and glass formulations that exhibit improved printability, allowing for finer resolution and improved control over the printed structures. Cement-based materials are particularly useful in construction-related applications, allowing for the rapid and efficient production of architectural components, building facades and even entire houses. Concrete mixtures are often optimised for 3D printing to ensure the material flows smoothly through the printer nozzle while maintaining its structural integrity and strength. Recent developments are exploring novel cement formulations with improved workability, setting times and mechanical properties. Additionally, efforts are also being made to incorporate sustainable and eco-friendly additives into the mixtures, such as recycled materials or alternative binders, to reduce environmental impact.

13 See Fiercely Contested and Full of Opportunities (mesago.com).

Figure 8

Trends in IPFs in AM materials, 2001–2020



Source: EPO

Many new and exciting applications of 3D printing have appeared in different industry sectors. The following trends provide insights into the evolving nature and potential areas of innovation in the application domains of additive manufacturing. The food industry represents the smallest domain with just 264 IPFs filed between 2001 and 2020 (see Figure 9). However, there has been a noticeable increase in food-related IPFs, particularly from 2016 to 2020, with 50 IPFs filed in 2020 alone. Customised chocolate confections, candy or vegetarian protein alternatives are just a few examples. AM allows for unique and visually appealing creations that mix various food materials, including sugar, dough or even mashed potatoes, and are difficult to achieve through traditional manufacturing methods. 3D printing technology is utilised to produce personalised nutritional supplements, tailoring the composition and dosage of vitamins, minerals and other nutrients based on individual needs. This enables precise and targeted supplementation for specific dietary requirements. Despite the potential of AM in the food industry, there are several technology challenges that are being tackled, such as identifying suitable food-grade materials that are safe for consumption, can be processed by 3D printers, and retain their properties during printing and storage. Achieving high printing resolution and speed while maintaining food safety standards is another challenge, and often cost-effectiveness and scalability of AM processes is an issue. Besides technical challenges, consumer acceptance and trust are critical for the widespread adoption of 3D-printed food.

The health and medical sector is emerging as the largest application domain, with nearly 10 000 IPFs over the 20-year period. Healthcare is recognised as one of the most significant user industries for additive manufacturing, and its impact continues to expand. With ongoing advancements in AM technologies and materials, patient care is being increasingly influenced by this disruptive technology. According to market research institute Research and Markets, the market for 3D printing in healthcare is projected to grow from $2.08 billion in 2021 to $5.59 billion by 2027, with an annual growth rate of approximately 18% (Research and Markets, 2023). Already, 3D printing is being utilised in a multitude of medical applications, such as the development of surgical incisions, drill guides, prostheses, and patient-specific replicas of bones, organs and blood vessels. Additionally, it enables customisation and personalisation of medical products, drugs and devices. The expansion of 3D printing in healthcare will be fuelled by societal and technological trends, including the ageing global population and the increasing prevalence of chronic diseases like cancer, respiratory and cardiovascular illnesses. Liver modelling, tissue engineering and the production of bone and medical implants are among the areas where 3D printing is expected to find broader applications in the future. Trends within the health and medical sector are provided in Box 4.

However, in recent years, the transportation sector has posed a challenge to the dominance of health and medical applications. In 2020, the transportation sector nearly matched the health and medical sector with 1 366 IPFs compared to 1 453 IPFs in health and medical applications, and totalling 7 177 IPFs between 2001 and 2020.

AM is not new to the transportation sector. Aerospace companies are using AM to produce lightweight and complex parts, leading to improved fuel efficiency and reduced emissions. Automotive manufacturers are leveraging AM for rapid prototyping, customised parts and production of lightweight structures. Additionally, the transportation sector benefits from AM in supply chain management, enabling on-demand manufacturing, reducing inventory costs and facilitating spare parts availability. High upfront production costs, limited material options and the need for industry-wide standards and certifications pose hurdles to widespread implementation in transportation. However, recent innovation trends aim to address these challenges. Ongoing advancements in AM technologies, such as multi-material printing and metal AM, expand the range of applications and improve part quality and performance. Moreover, research focuses on developing sustainable materials and processes, as well as enhancing automation and post-processing techniques. Trends within the transportation sector are provided in Box 5.

Machine tooling, with approximately 7 000 IPFs, and the energy sector are two other robust application domains for AM. These domains have witnessed significant growth since 2013, although their growth dynamics have slowed in recent years.

Machine tooling often involves complex geometries and low production quantities, making additive manufacturing a suitable choice. One of the long-standing applications of 3D printing in machine tooling has been the production of master patterns for mould creation. Any AM technology can be employed to generate these master patterns. Moreover, AM also enables the integration of conformal cooling channels within tooling, allowing for efficient heat dissipation. These channels lead to shorter moulding cycle times, increased tool lifespan and improved part quality. Examples of tools benefiting from AM include jigs, fixtures, gauges, as well as drilling and cutting guides. Recent advancements in multi-material printing enable the production of tooling with integrated functionalities, such as incorporating sensors or heat-resistant properties. Metal AM technologies, such as powder bed fusion and directed energy deposition, are being utilised to create high-performance tooling components with improved durability and precision. These recent innovations in AM for machine tooling are driving its adoption by manufacturers, offering cost-effective and time-efficient solutions for producing complex and customised tooling equipment.

While the energy sector has been utilising AM for repairing worn and broken parts and creating prototypes, recent innovation developments have expanded its potential. As the focus shifts towards a greener future, AM is being leveraged to enhance renewable technologies such as wind turbines and batteries. The power and energy industry finds AM appealing due to its ability to reduce physical inventories and accelerate production. AM enables spare parts to be created on demand and facilitates digital inventory management, providing enhanced flexibility and efficiency. These advancements in AM are enabling the power and energy sector to optimise its operations, enhance sustainability and drive innovation in renewable technologies.

In contrast, the electronics industry, which was on par with machine tooling and energy sectors a decade ago, has not experienced the same growth dynamics in AM-related patent filings with just under 2 000 IPFs between 2001 and 2020. While the initial hype around 3D printing in the field of electronics has cooled, gradual progress is being made towards industrial use. The applications of 3D-printed electronics are diverse and expanding, ranging from efficient electric motors to antennas for spaceflight. Despite challenges, such as the complex manufacturing process involved, progress is being made. Companies and research institutes are exploring the incorporation of electronic components into the 3D printing process itself, allowing for greater flexibility in product customisation and the integration of functional elements. As the technology matures and becomes more polished, the market for 3D-printed electronics is expected to grow, with significant potential in areas such as circuit boards and chips. However, achieving certified products and achieving higher efficiency and larger production runs will require time and further development.

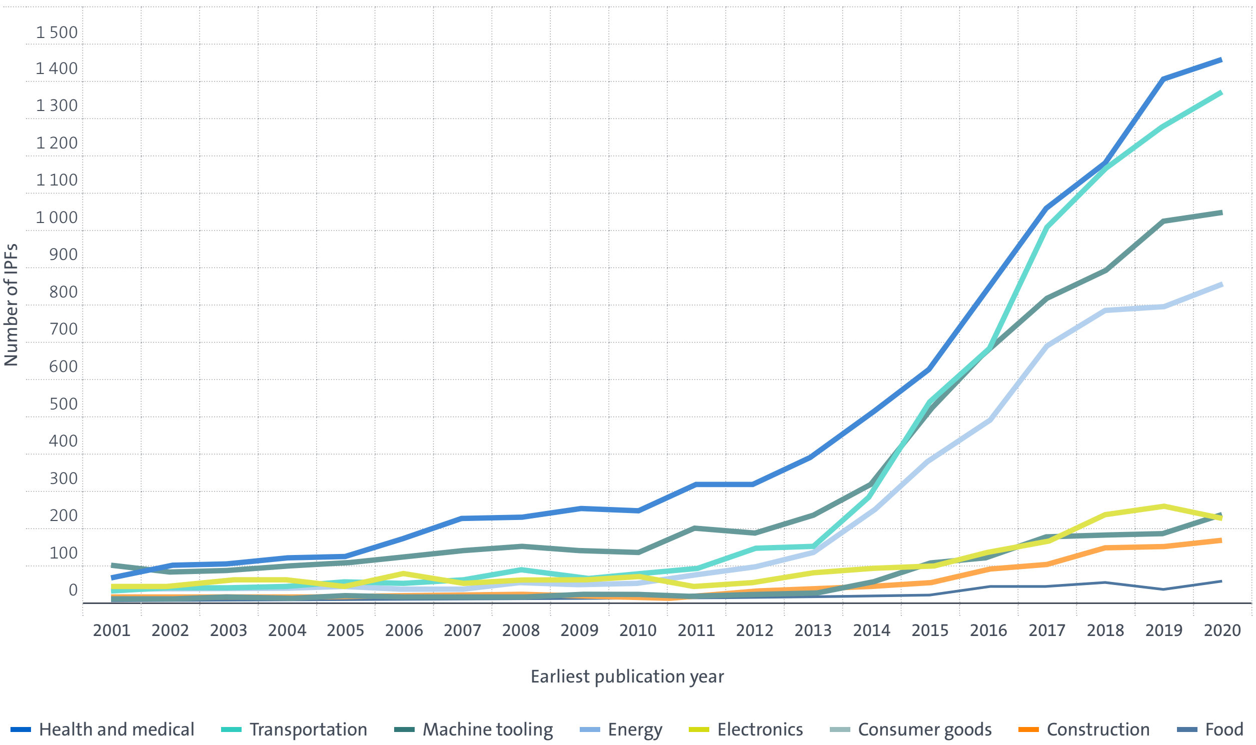
While consumer goods and construction remain relatively small application domains, they have exhibited strong growth in recent years. Both domains have seen a notable increase from less than 25 IPFs in 2013 to 230 IPFs for consumer goods and 163 IPFs for construction in 2020.

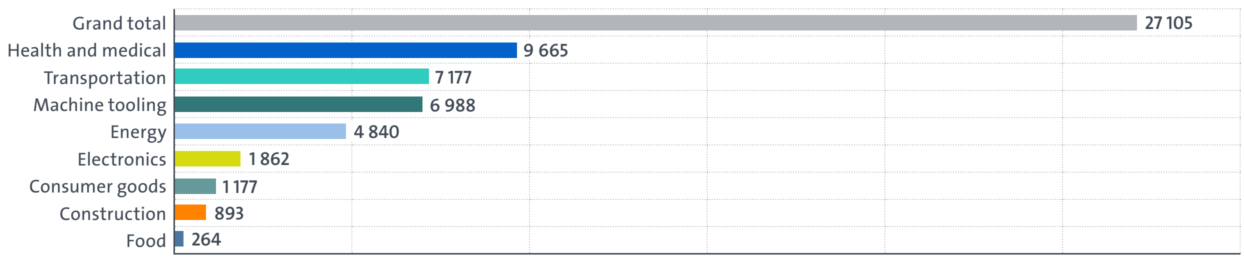
AM has gained significant traction in the consumer goods industry. This innovative technology is being utilised to produce a wide range of consumer products, including eyewear, footwear, fashion, jewellery and sports equipment. Many companies are adopting AM for its ability to accelerate time to market, and create complex and unique shapes and geometric features, making products lighter and stronger. AM also enables mass customisation in the consumer market. By employing 3D scanning and printing technology, manufacturers can develop personalised products like customised 3D-printed ski boots or helmets. Currently, polymer-based AM dominates consumer product manufacturing, but new developments are making the use of metal additive manufacturing more accessible and cost-effective.

The use of AM technologies in the construction industry has witnessed significant advancements in recent years. There has been a surge in dedicated systems and services, driving the expansion of additive construction capabilities. Companies can now successfully produce multi-storey structures, bridges and other large-scale AM applications. The development of standards plays a crucial role in enabling adoption in construction. In 2023, the publication of the ISO/ASTM 52939 standard marked a significant milestone. This standard outlines the requirements necessary for the production and delivery of high-quality additively constructed structures for residential or infrastructure applications. Currently, the focus in additive construction innovation revolves around optimisation, enhanced design flexibility, reduced construction time and increased sustainability in building projects.

Figure 9

Trends in IPFs in AM application domains, 2001–2020





Source: EPO

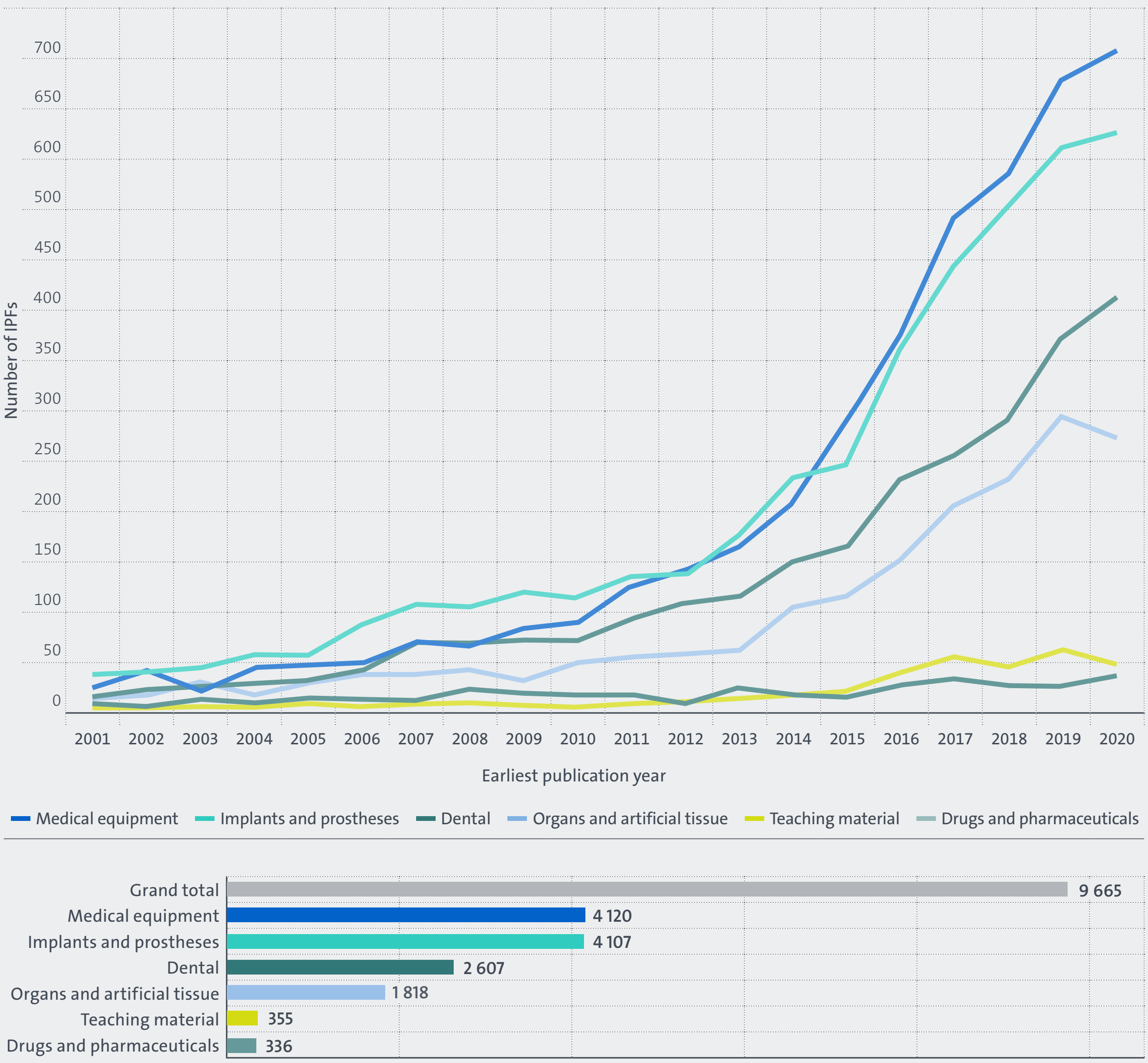
Box 4: AM in health and medical

The medical and health sector is particularly prone to additive manufacturing applications and development due to several factors. One key factor is the inherent variability of the human body, where each individual has unique anatomical structures and requirements. Traditional manufacturing methods often struggle to provide personalised solutions, as medical devices are typically made in standard sizes. However, additive manufacturing opens up new possibilities in medical device design and production by enabling customisation and patient-specific solutions. The ability to create highly customised products, such as anatomical models, virtual surgical planning tools and patient-specific implants, has transformed the medical landscape.

In addition to traditional manufacturing settings, additive manufacturing has found widespread use in hospitals and the medical device industry. The concept of hospital and clinic-based manufacturing, also known as point-of-care (POC) manufacturing, has gained traction. POC manufacturing involves the production of patient-matched devices within the healthcare facility itself, allowing for efficient and on-demand manufacturing. As of today, the Food and Drug Administration (FDA) in the US has cleared over 250 medical devices made using additive manufacturing (Wohlers Associates, 2023).

Figure 10

Trends in IPFs in health and medical applications, 2001-2020



Source: EPO

In the early 2000s, medical equipment, and implants and prostheses emerged as the largest fields for AM applications in health and medical (see Figure 10). Both fields witnessed significant growth, with medical equipment experiencing an even steeper trajectory. By 2020, medical equipment reached over 650 new IPFs, marking a five-fold increase in less than a decade, while implants and prostheses grew four-fold since 2012 to 574 IPFs. Throughout the 20-year period from 2001 to 2020, a total of over 4 100 IPFs were published for AM applications related to medical equipment, and implants and prostheses respectively.

In medical equipment, Johnson & Johnson is leading with 115 IPFs, protecting inventions such as customised surgical instruments (see Figure 11). AM also facilitates the creation of surgical guides, templates and models for accurate surgical planning and execution, particularly in procedures like corrective osteotomies and joint replacements. Another typical application of AM technology is the production of patient-specific anatomical models, allowing surgeons to visualise complex anatomy before surgery, refine surgical plans and simulate procedures. By converting volumetric medical imaging data, such as computed tomography or magnetic resonance imaging into 3D printing file formats, physical anatomical models can be created at full scale. These models serve as invaluable tools during surgeries, providing a reference guide and improving surgical precision.

Johnson & Johnson is also among the leaders in implants and prostheses, with 76 IPFs. By leveraging the capabilities of AM, the production of implants and prostheses can be tailored to individual patients, leading to enhanced patient outcomes and improved quality of life. For implants, 3D printed anatomical models have been instrumental in producing patient-matched implants for over two decades. These models are created based on medical imaging data, allowing for precise customisation and design. The ability to create implants with complex shapes and features makes additive manufacturing an ideal technology for producing personalised implants that fit perfectly with the patient's anatomy. Personalised implants have found use in various surgical procedures, such as neurological surgeries, plastic and reconstructive surgery, and oral surgeries. AM is increasingly being used for producing polymer and metal medical devices, enabling serial production of orthopedic implants with complex and porous structures that promote bone ingrowth and are lightweight. This technology is particularly beneficial for applications such as spinal fusion devices; these may take the form of, for example, spinal cages, hip cups or gap-filling wedges for extremities, providing improved bone preservation, faster surgeries and recoveries. AM has also found remarkable applications in the field of eyecare, exemplified by EssilorLuxottica's impressive 85 IPFs, who is a renowned specialist in optical lenses. Additionally, AM is used to optimise the acoustic properties of hearing aids. With 3D printing, intricate internal structures and channels can be designed to enhance sound amplification and control. Another notable application is the production of custom-fit ear shells using 3D printing technology. By scanning the patient's ear canal and converting the data into a 3D printing file format, hearing aid manufacturers can create personalised ear shells that perfectly match the individual's ear anatomy. One of pioneers is the Swiss hearing care company Phonak, one of the top applicants with 37 IPFs in this area.

Dental applications represent the third-largest field within the medical sector, with over 2 600 IPFs published between 2001 and 2020. The field also exhibited strong growth recently, with IPFs per year increasing from 162 to over 400 between 2015 and 2020. The dental industry has embraced 3D printing technology for various applications, revolutionising traditional procedures and simplifying processes. Dental surgeries and laboratories have leveraged 3D printing for surgical guides, models, aligners and implants, among others. The availability of additive manufacturing has streamlined orthodontic appliance creation by utilising 3D data obtained through intraoral scans or radiological imaging. This data serves as the foundation for designing and 3D printing dental parts, enabling precise customisation and fit. As dental-specific desktop 3D printers become faster, more user-friendly and affordable, there is a growing industry goal of implementing chairside 3D printing within dental surgeries. In the dental area, several companies have made notable contributions. Among them, the US multinational conglomerate 3M is the applicant of 184 IPFs between 2001 and 2020. Additionally, two companies specialising in innovative dental solutions have made their mark: the US-based company Align Technology (123) and the Liechtenstein-based company Ivoclar (61), securing the second and third positions in terms of IPFs.

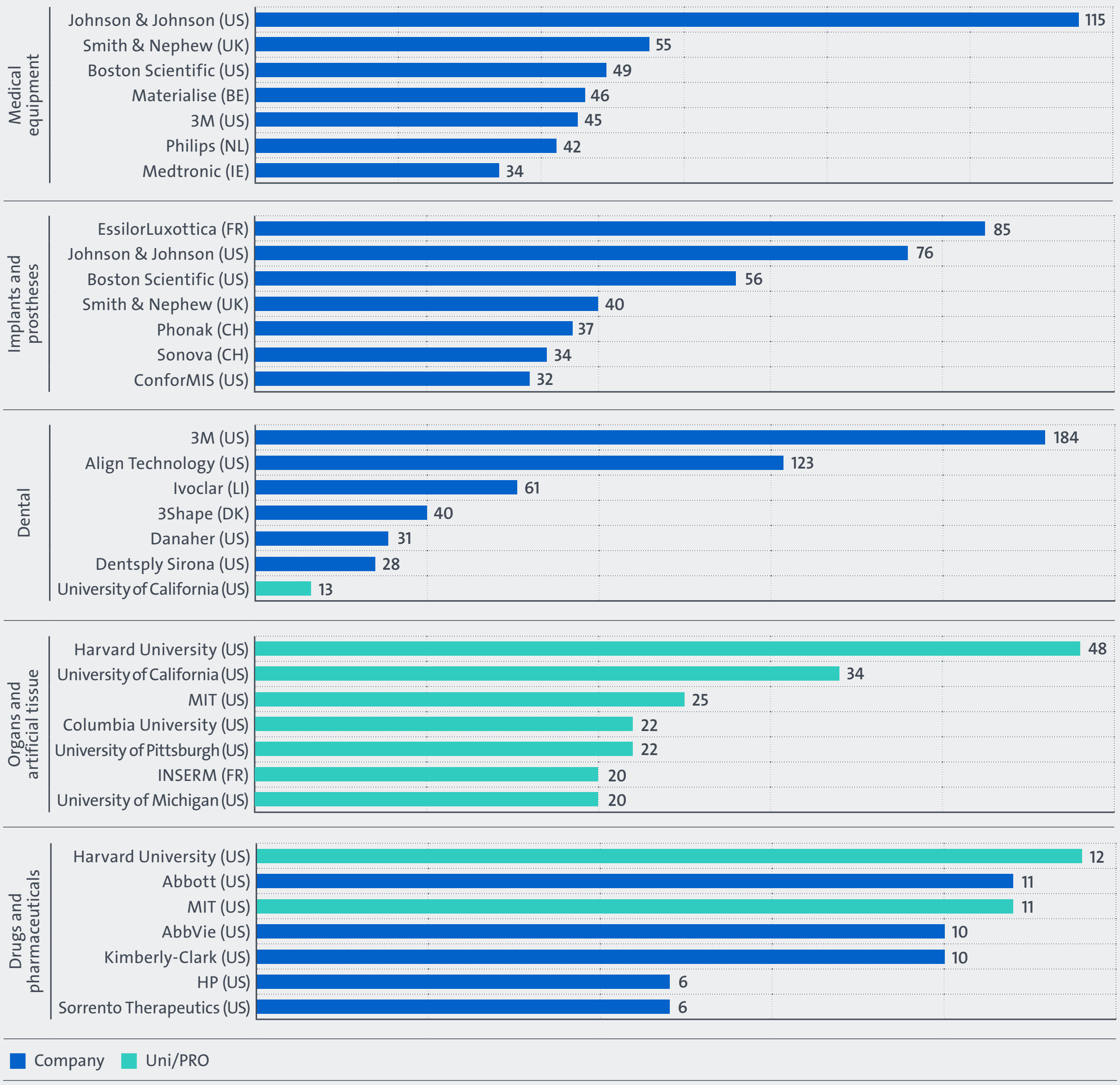
Organs and artificial tissue emerged as the fourth-largest field, with approximately 1 800 IPFs during the same period. Notably, there was substantial growth in IPFs between 2013 and 2019, although a slight decrease to 271 IPFs was observed in 2020. Scientists and biomedical engineers are exploring the potential of 3D printing technology to create patient-specific organs and tissues that can be used for transplantation and tissue repair. This cutting-edge technology allows for the precise fabrication of complex structures, such as blood vessels, heart valves and even human organs, using bio-inks and living cells. Despite these exciting developments, there are still several challenges that need to be overcome before additive manufacturing of organs and artificial tissue can reach the market. One of the primary challenges is the complexity of recreating the intricate microarchitecture of organs, such as the vascular network, which is crucial for the proper functioning of the transplanted tissue. Ensuring that the 3D printed organs integrate seamlessly with the recipient's body and receive adequate blood supply remains a significant obstacle. Another critical aspect is the need for biocompatible and bioresorbable materials that can be safely implanted into the human body without causing adverse reactions. Furthermore, as with most medical devices, the field of additive manufacturing of organs and artificial tissue is subject to stringent regulatory requirements and ethical considerations. Extensive testing and validation are essential to ensure the safety and efficacy of 3D printed organs before they can be approved for clinical use.

On the other hand, teaching materials as well as drugs and pharmaceuticals accounted for the smallest fields, with 355 and 336 IPFs respectively between 2001 and 2020. In each field, fewer than 50 IPFs were published in 2020. 3D printing offers unique opportunities to create realistic and patient-specific anatomical models that can be used for educational and training purposes. These 3D printed teaching materials allow medical students, healthcare professionals and even patients to gain a better understanding of complex anatomical structures and medical procedures. They can be used to simulate surgical scenarios, practice intricate techniques and improve surgical planning. Despite the potential benefits, the market for additive manufacturing of teaching materials in the healthcare sector remains relatively small and underdeveloped. However, the technology and materials required for high-fidelity anatomical models can be expensive, making it a less accessible option for many educational institutions and healthcare facilities with limited budgets. Furthermore, educational institutions and healthcare facilities may not yet fully understand the potential value and benefits of incorporating 3D printed teaching materials into their curricula.

One notable area of research in drugs and pharameceuticals is the development of personalised medicine, where 3D printing is utilised to create patient-specific dosage forms. This technology allows for precise control over the drug's composition and release rate, tailoring treatments to individual patients' needs and improving therapeutic outcomes. Additionally, 3D printing has facilitated the production of complex drug delivery systems, such as multi-layered tablets, enabling more efficient and targeted drug delivery. Another emerging application is the creation of patient-tailored drug combinations, where multiple medications can be combined into a single dosage form. This approach simplifies medication regimens, enhances patient compliance and optimises drug interactions. Furthermore, 3D printing has shown potential in creating personalised drug-eluting devices for localised treatment, particularly in areas like wound healing and tissue regeneration. Currently, universities such as Harvard University and MIT, but also large pharmaceutical companies such as Abbott and AbbVie are protecting their inventions in this field (see Figure 11).

Figure 11

Top applicants in selected health and medical applications, 2001–2020



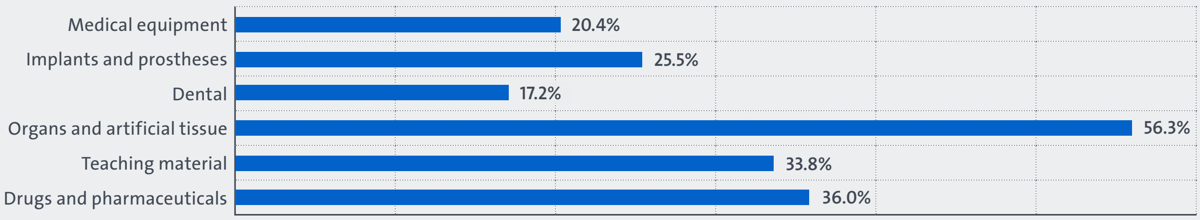
Source: EPO

Despite these exciting advancements, additive manufacturing in drugs and pharmaceuticals is still an emerging technology with several barriers to overcome. One major challenge is ensuring the safety and quality of 3D printed medications. The regulatory landscape for pharmaceutical manufacturing using additive techniques is evolving, and stringent quality control standards need to be established to guarantee consistent and reliable drug products. Additionally, the selection of suitable materials for drug printing and their interactions with the human body require extensive research and validation.

The health and medical sector displays significant contributions from universities and public research organisations (PROs), representing nearly one in every four IPFs. However, variations exist among the different application fields within health and medical (see Figure 12). Dental and medical equipment exhibit the lowest involvement of universities and PROs, with shares around or below 20%. This suggests that these fields are more mature and closer to market implementation. In contrast, organs and artificial tissue witness over half of the IPFs stemming from universities or PROs. It is, therefore, not surprising that all top applicants in this field are either universities or PROs. Harvard University is the largest applicant with 48 IPFs in this field, followed by the University of California (34) and MIT (25). The only non-US institution is the French institute INSERM with 20 IPFs. For drugs and pharmaceuticals, teaching materials, and implants and prostheses, approximately one in every three IPFs originates from universities or PROs, highlighting their significant contributions to innovation in these fields.

Figure 12

Share of universities and PROs in health and medical, 2001–2020



Source: EPO

Box 5: AM in transportation

Additive manufacturing has become an integral part of the aerospace and aeronautics industry, emerging as the largest application field within Transportation (see Figure 13). With over 4 500 IPFs between 2001 and 2020, its development has witnessed significant acceleration, especially between 2013 and 2017, where IPFs per year surged from under 100 to over 700 in just four years. As shown in Figure 14, this was largely driven by contributions from two US aviation companies Raytheon Technologies, with 957 IPFs between 2001 and 2020, and General Electric (848 IPFs), who are by far the largest applicants in the field, but also from several European players, such as Rolls Royce (293 IPFs), Siemens (292 IPFs), Safran (251 IPFs) and Airbus (184 IPFs). Although the growth rate has moderated since then, the field continues to advance steadily, reaching 834 IPFs in 2020 alone.

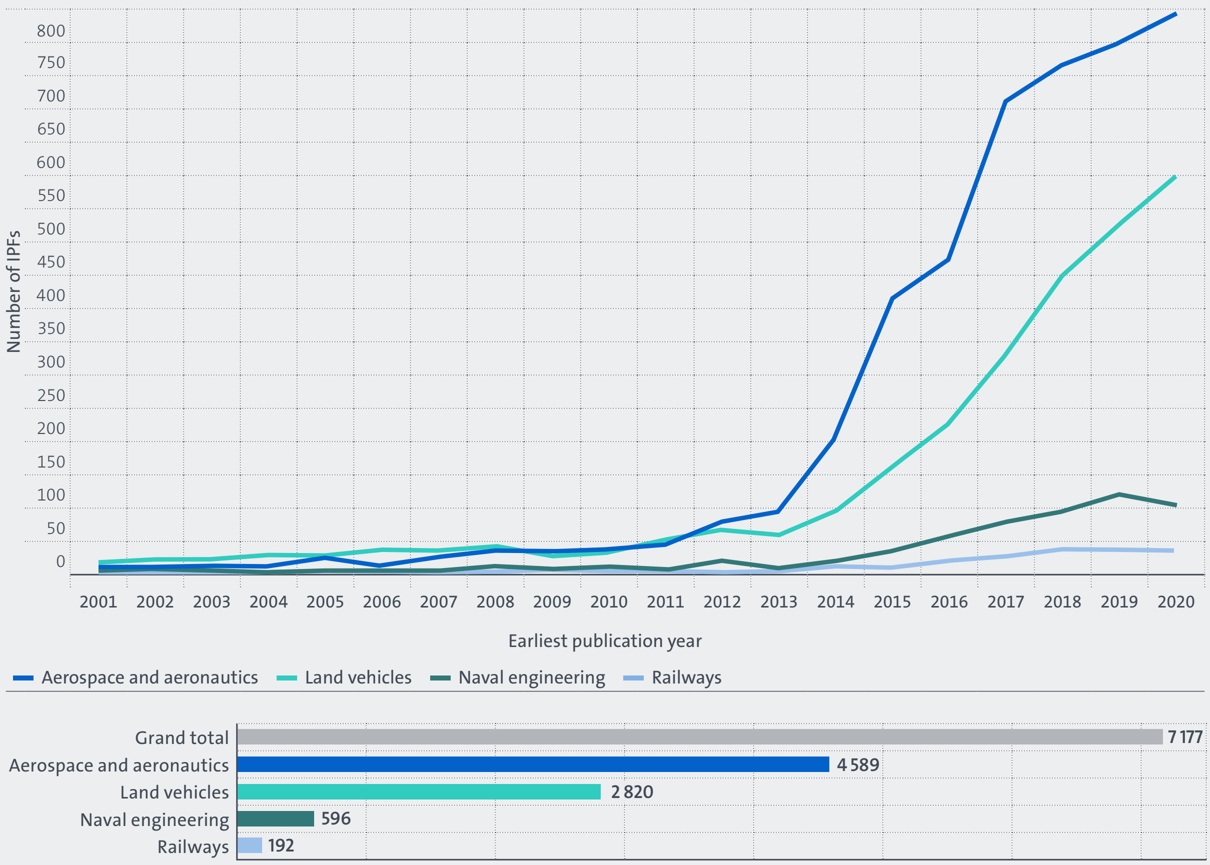
The aerospace industry was among the early adopters of additive manufacturing, leveraging its capabilities to produce lightweight parts that contribute to reduced weight, fuel consumption and emissions. The ability to create intricate geometries and lightweight parts has led to significant improvements in aircraft performance, fuel efficiency and overall sustainability. For instance, complex components like turbine blades, fuel nozzles and air foils are now 3D printed with materials like titanium and composites, enabling better aerodynamics and reduced weight.

This technology has revolutionised various aerospace applications, encompassing prototyping, repair, maintenance, tooling, and research and development activities. One of the primary advantages of additive manufacturing lies in its ability to provide superior value in low-volume production. It has streamlined supply chains, reduced material wastage and enabled rapid prototyping, leading to faster innovation and reduced development costs. Notably, dozens of aerospace and space start-ups have thrived, bringing innovative products to market, facilitated by AM's elimination of the need for scale economies.

As the aerospace and space sectors continue to explore and harness the potential of additive manufacturing, its impact on the industry is expected to grow even further. However, despite its transformative potential, aerospace and aeronautics faces several challenges in adopting AM technologies more widely. First, as in the healthcare sector, there is a need for standardisation and certification of materials and processes to ensure the reliability and safety of printed components. The stringent regulatory environment in aviation demands rigorous testing and validation, which can be time-consuming and costly. Additionally, the high initial costs of AM machines and materials can present a barrier for smaller aerospace companies, limiting their access to the technology.

Figure 13

Trends in IPFs in transportation applications, 2001–2020



Source: EPO

Land vehicles, which include both automotive applications and vehicles without motors such as bicycles, have embraced AM technologies with a total of 2 820 IPFs between 2001 and 2020. Although the growth in this area was not as rapid as in Aerospace and aeronautics, it still showed considerable progress. From 2013 to 2020, the annual number of IPFs increased ten-fold, surging from 59 IPFs to almost 600.

In the automotive industry, additive manufacturing has been in use for several decades, initially focused on concept modelling and prototyping. Today, automotive companies leverage AM for design validation, fit and function testing, as well as certain types of tooling. However, its use for final part production is mainly limited to low production volumes for high-end vehicles. On the other hand, the automotive racing industry has actively adopted AM to enhance the performance and efficiency of race cars. Many original equipment manufacturers (OEMs) and automotive suppliers have made substantial investments in AM capacity to offer personalised options, catering to individual customer preferences. The two OEMs Ford Motor Company and General Motors, with 123 and 69 IPFs, respectively, together with the German automotive supplier Bosch (77) are the three largest applicants in this application field (see Figure 14). In the military and defence sector, additive manufacturing has facilitated the production of spare parts on-demand, reducing logistics challenges and maintenance costs for armoured vehicles. Raytheon Technologies is also among the top applicants here.

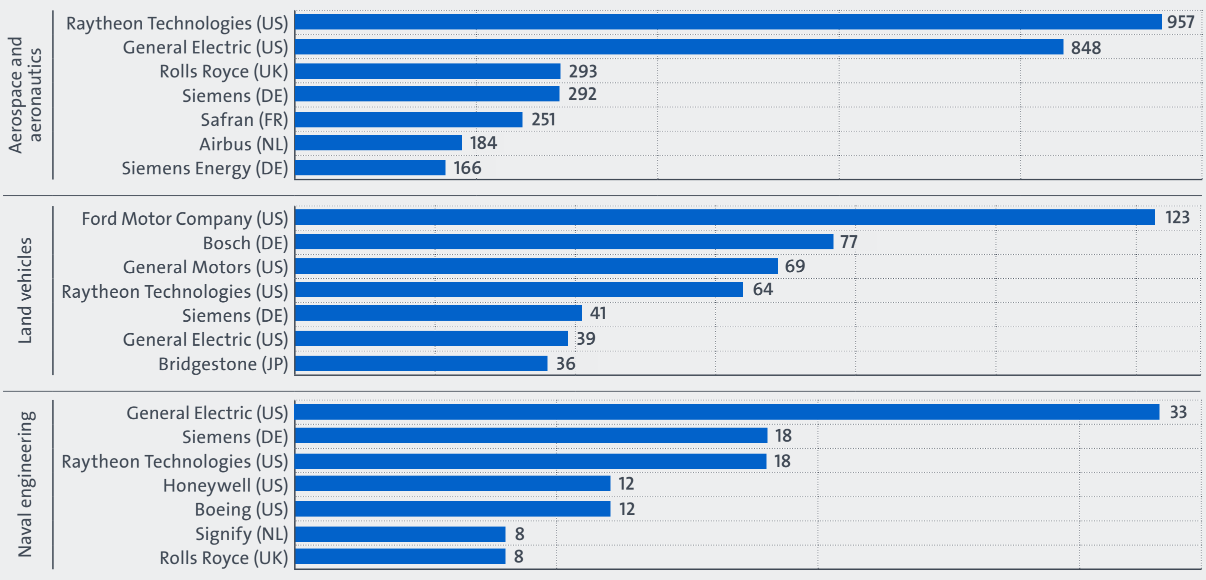
Despite its evident advantages, there are several challenges to broader adoption of AM technologies in the land vehicles sector. One significant obstacle, and similar to aerospace and aeronautics, is the need for standardised and certified materials suitable for use in critical components. Ensuring the reliability and durability of 3D printed parts is crucial in high-stress applications like automotive and defence vehicles. Additionally, the relatively slow production speed of additive manufacturing processes can hinder large-scale production, especially in automotive, making it less feasible for mass-produced consumer vehicles.

Naval engineering and railways are relatively small application fields for AM technologies, with 596 and 192 IPFs respectively. While naval engineering has shown faster growth compared to railways, with just over 100 IPFs in 2020, both sectors are significantly less developed than aeronautics and aerospace, and land vehicles. Railways, in particular, have seen limited adoption, with only around 35 IPFs related to AM. As the technology continues to advance, there may be potential for further growth and innovation. AM allows naval engineers to optimise designs for enhanced performance and efficiency, and has reportedly been employed to create propellers and brackets, among other components. One of the main barriers to its adoption is the scalability of additive manufacturing for large naval vessels and the associated high costs of acquiring and maintaining advanced 3D printers. The top applicants in naval engineering are General Electric (33 IPFs), Siemens (18) and Raytheon Technologies (18).

Some notable examples of AM in railways include the creation of replacement parts for legacy systems that may no longer be available through conventional suppliers, as well as the development of specialised components that improve fuel efficiency and reduce maintenance requirements. Additionally, the ability to 3D print lightweight and strong materials allows for the design and production of more aerodynamic train components, which can contribute to energy savings and improved sustainability. The challenges to adoption of AM in railway applications are very similar to other transportation sectors. To overcome these challenges and fully harness the potential of AM, collaboration between industry stakeholders, regulatory bodies and technology providers is essential to advance technological development, establish best practices, standards and streamlined processes.

Figure 14

Top applicants in selected transportation applications, 2001–2020



Source: EPO

Several trends can be observed across the seven AM techniques outlined in the ISO/ASTM52900:2021 standard. These trends highlight the evolving landscape of AM technologies and the shifting focus of innovation within the industry. As can be seen in Figure 15, developments in vat photopolymerisation have consistently dominated the AM landscape, as it was the first patented and commercialised AM process. Between 2001 and 2020, the number of IPFs totalled nearly 13 000. The AM systems are used predominantly to produce high-resolution parts at a reasonable cost using polymers, ceramics and metals.

In more recent years, powder bed fusion has emerged as the clear second largest AM technique, gradually closing the gap with vat photopolymerisation and reaching an annual IPF count of almost 1 700 in 2020. It can be used for a wide range of polymers and metals. Power bed fusion systems are still considered relatively complex with high operating and feedstock costs compared to other 3D printing systems. However, since it is able to produce the desired part quality and mechanical properties needed for final manufacturing applications, companies are investing in process time and cost reduction.

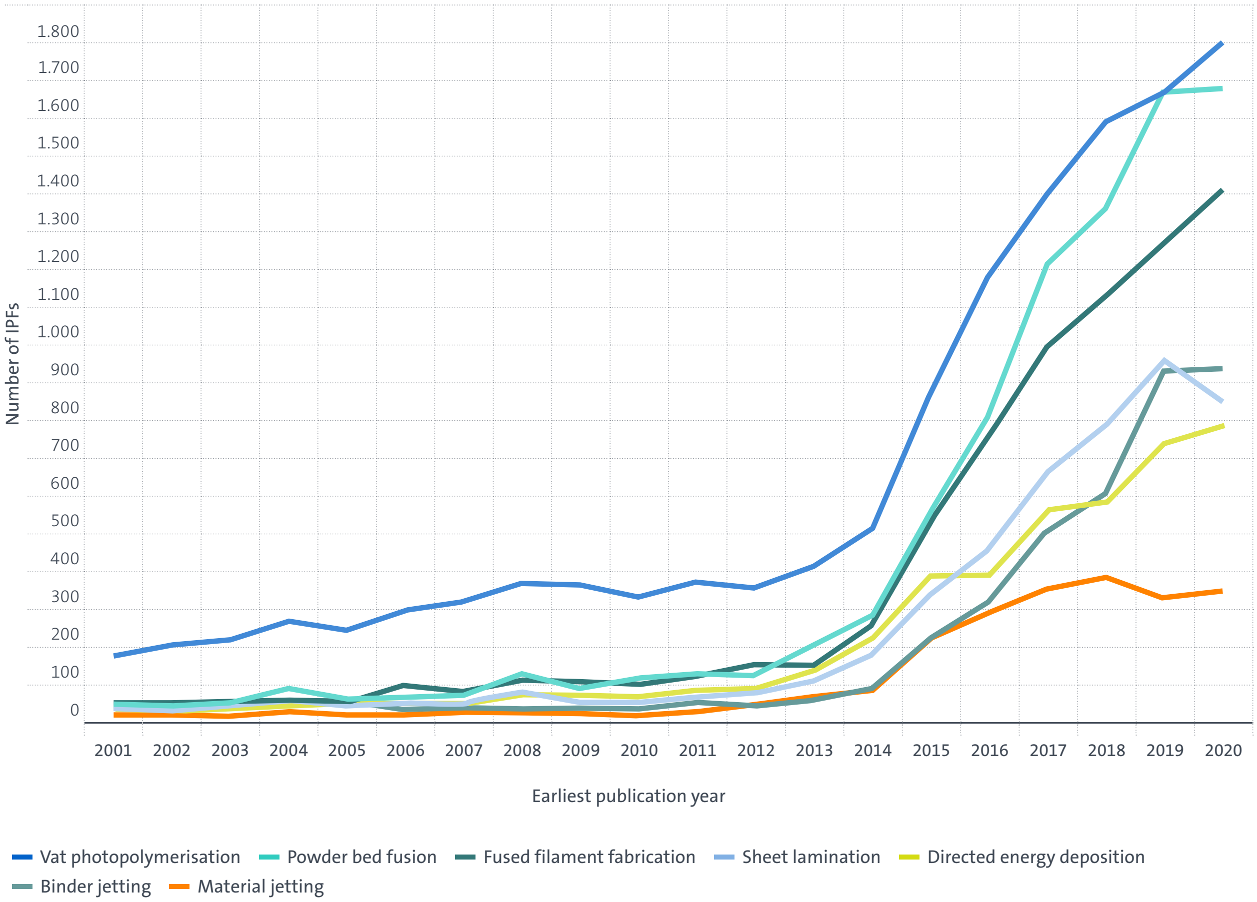
Fused filament fabrication, also called material extrusion, follows as the third most important AM technology, boasting over 7 500 IPFs over the span of two decades and over 1 400 IPFs in 2020 alone. The first commercial process was introduced as early as 1991 and used for a wide range of feedstock, such as thermoplastics, ceramics, concrete, composites, chocolate and living cells suspended in a hydrogel. More recent developments also focus on metals. Fused filament fabrication systems are very versatile, affordable and user-friendly, and find applications making them widely accessible and easy to operate. They are used in various industries, including furniture manufacturing, electronics, food industry and construction. It is therefore not surprising that it is currently considered as the most favoured 3D printing method by the industry, even before vat photopolymerisation (see Hubs, 2023).

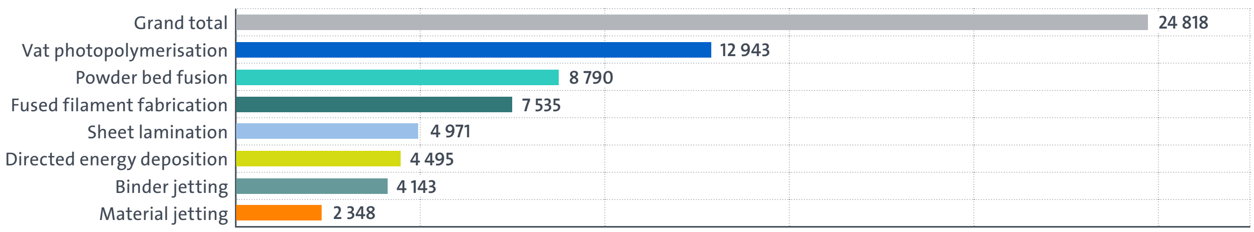
Sheet lamination and directed energy deposition trail behind with approximately 5 000 and 4 500 IPFs, respectively. Directed energy deposition systems use metal powder or wire as feedstock to produce small or large metal parts. The technique offers certain unique properties. It can deposit more than one material while simultaneously creating composite materials with different structural properties; furthermore it can produce curved layers, which makes it suitable for repair jobs or adding features to existing objects. Sheet lamination is a process where sheets of material, such as paper, metal foils or fibreglass sheets, are bound together to create an object. Innovations are underway to improve the surface finish and texture of sheet lamination prints, as well as methods to integrate functional elements into sheet lamination prints, such as embedded sensors, or electronic components, but also to expand the range and mechanical properties of existing materials.

While binder jetting and material jetting were initially both very small fields, material jetting has experienced substantial growth, becoming the fourth largest AM technology category by the number of IPFs published in 2020, whereas material jetting developments have stagnated since 2017. Material jetting typically uses photopolymers and wax-like substances, however, the most recent developments also experiment with metals. It is often used to create patterns or moulds for investment casting processes. Binder jetting and material jetting are AM techniques that utilise inkjet print heads. However, in binder jetting, the dispersed material serves as a binding agent to solidify the feedstock material and create the desired product, whereas in material jetting, the dispersed material directly forms the main building material itself. Binder jetting is a relatively fast and cost-effective printing technique compared to other AM processes, and also highly scalable, since it can produce small as well as large objects.

Figure 15

Trends in IPFs in AM machines and processes, 2001–2020





Source: EPO

AM is a digitally driven technology. Therefore, digital technologies represent a vital part within the realm of AM, encompassing a range of innovative advancements. Despite being the smallest among the four AM technology sectors, digital technologies have exhibited the most rapid growth since 2013 (see Figure 6).

This surge is primarily attributed to novel inventions in the control and monitoring of the AM printing process (see Figure 16), such as the integration of advanced sensors and machine vision technologies, which ensures the accuracy, quality and reliability of the printing process. These systems provide real-time feedback, allowing operators to monitor various parameters such as temperature, pressure, material flow, defects or deviations from the digital model, and build progress. By continuously monitoring these variables, control systems can detect anomalies or deviations from the desired specifications, enabling timely adjustments or interventions. This capability is vital for maintaining consistent print quality and minimising defects or errors. The years 2019 and 2020 alone witnessed the publication of over 3 000 IPFs, reflecting the dynamic nature of this field.

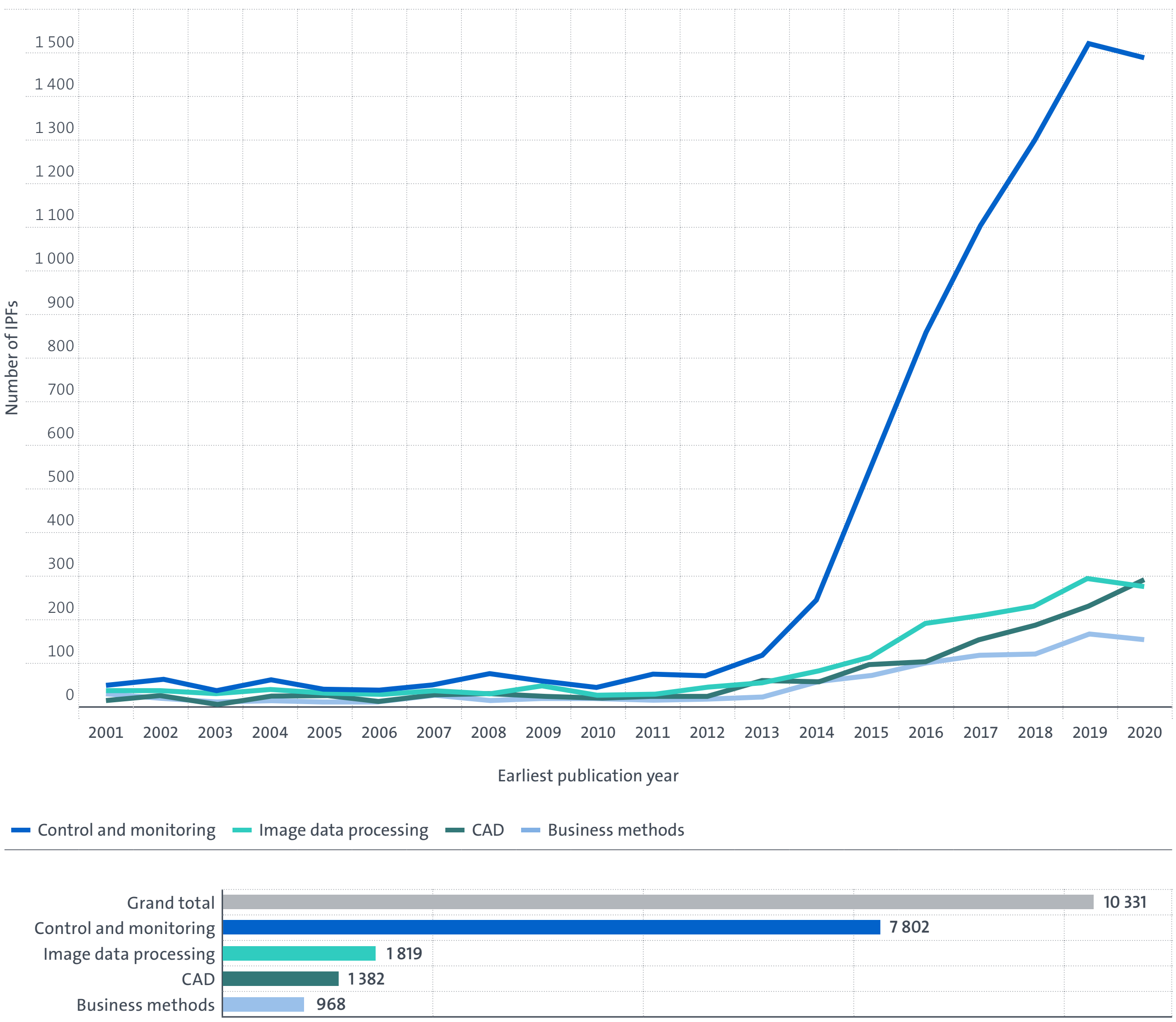
This trend is driven by several factors, such as the complexity and intricacy of AM processes that demands advanced monitoring capabilities to maintain quality and consistency. As AM technology evolves and is adopted in more industries, the need for reliable control systems becomes increasingly crucial. Secondly, the integration of digital technologies and connectivity has enabled the collection and analysis of vast amounts of data, enabling better understanding and optimisation of the printing process. The ability to monitor and control AM systems remotely also offers greater flexibility and efficiency. Finally, the demand for quality assurance and certification in additive manufacturing, particularly in industries like aerospace and medical, has fuelled the development of sophisticated control and monitoring systems to meet stringent standards.

Within the digital technologies domain, image data processing, computer-aided design (CAD) and business methods, constitute relatively small technology fields with less than 2 000 IPFs each. Among these three, CAD, which is crucial to create and design printable 3D models, demonstrates the swiftest growth, with almost 300 IPF in 2020, indicating its increasing significance and application within the AM landscape. CAD allows designers and engineers to create detailed and complex 3D models of objects that can be directly translated into printable files for additive manufacturing systems. The importance of CAD lies in its ability to streamline the design process, enabling rapid iteration, customisation and optimisation of parts. Recent developments focus on generative design algorithms that utilise artificial intelligence and optimisation techniques to generate design solutions based on specified performance criteria. This approach enables the creation of highly efficient and lightweight structures, reducing material usage and production costs while maintaining or enhancing strength. Another area of development is the integration of CAD software with simulation tools, which helps optimise part orientation, material selection and support strategies, resulting in improved print success rates and overall quality. Furthermore, CAD software is becoming more user-friendly and accessible to a broader range of users in various industries. As more professionals with diverse backgrounds adopt additive manufacturing, the need for intuitive CAD tools that facilitate easy design creation and modification becomes paramount.

Conversely, the development of image data processing and business methods has been exhibiting comparatively less dynamism since 2013, highlighting the varying rates of innovation within different aspects of digital technologies in additive manufacturing. Image data processing is needed to translate digital files, such as medical images, for example, into an AM file format. This process is crucial for an efficient and accurate AM workflow and heavily applied in medical care. Examples of business methods are decision support systems to evaluate cost structures of AM processes and to select the right material, systems to optimise the design and quality of an object, but also management and security systems for the AM value chain, such as digital warehouses and on-demand spare part production.

Figure 16

Trends in IPFs in digital AM technologies, 2001–2020



Source: EPO

Heated chamber on the Roboze production printer

Case study: ROBOZE

Company:	Roboze S.p.A
Locations:	Italy, Germany, US
Founded:	2013
No. of employees:	120
Products:	3D printers, proprietary materials and software

"Patents are the natural consequence of innovation in a company."
Alessio Lorusso, CEO and founder, Roboze

Building an innovation ecosystem with IP

Roboze[14] is a 3D printing firm founded in Italy in 2013. The company's high-precision technology is capable of processing super polymers and composite materials into finished functional parts for use in the most extreme conditions and sectors. Roboze also provides a global service network, which enables the on-demand printing of custom parts and enhanced supply chain sustainability. Since its inception, the company has used patents and intellectual property rights as strategic tools to grow and secure its future.

Reshaping supply chains

A passionate motorsport enthusiast, Alessio Lorusso began his journey in additive manufacturing at just 17 when he built his first beltless 3D printer. This innovation was the first step to founding Roboze in the coastal city of Bari. In little over seven years, the company has leveraged its patented inventions to become a global leader in the field, with customers in 25 countries and additional facilities in Germany and the US.

The beltless printer incorporates mechatronics, similar to that used in CNC machines[15], enhancing the reliability and accuracy of 3D printing. Lorusso and his team have also developed super polymers and composite materials compatible with their printing process. As a result, Roboze has been able to exploit new opportunities in sectors like aeronautics and aerospace, energy, and health and medical.

The company's ecosystem comprises 3D printers, proprietary materials and software. It also offers manufacturing as a service through a global distributed manufacturing network. The network connects 3D printers with potential customers nearby, ensuring that parts can be printed close to point-of-use. Moving to distributed production reduces warehouse costs, shipping expenses and associated CO_2 emissions, while also enabling greater customisation and fast turnaround times.

Listening to market demands

"Our IP strategy is designed to attract smart money"

Strategic IP protection has been an essential element in Roboze's growth and may be the key for its potential for long-term success. The company began filing patent applications early on and looks to protect both its machines and the printing process itself. The precise chemical composition of materials remains a trade secret, and copyright and trademarks are used to cover its software and branding. Roboze's market intelligence activities include an ongoing review of IP in the additive manufacturing field. This not only helps the company benchmark against competitors, but also enables it to identify potential infringement.

Roboze has filed over ten patent applications for their 3D printing process, helping to secure funding from over 15 investors in Europe and the United States. Moreover, many of Roboze's customers are in highly regulated industries. While such customers may prefer to form long-term partnerships with suppliers, they also need to qualify products or services before entering into an agreement. Their assessment often includes an inspection of patents, which lend credibility and demonstrate research and development.

Defensive patenting forms an important part of the company's IP strategy, and it also looks to safeguard its future interests. Some of Roboze's patented inventions may not currently be feasible from a commercial perspective, however, having IP in place could enable the company to pivot quickly if the additive manufacturing field shifts.

14 Live case study presentation by Alessio Lorusso at HTB conference March 2022: https://www.youtube.com/watch?v=anq7uE6yUwk. Q&A with global expert panel and live case study speaker: https://www.youtube.com/watch?v=mmxMvHWj3g4.

15 CNC (computer numerical control) machines are machine tools that cut or move material as programmed on the controller.

4. Global and European AM innovation centres

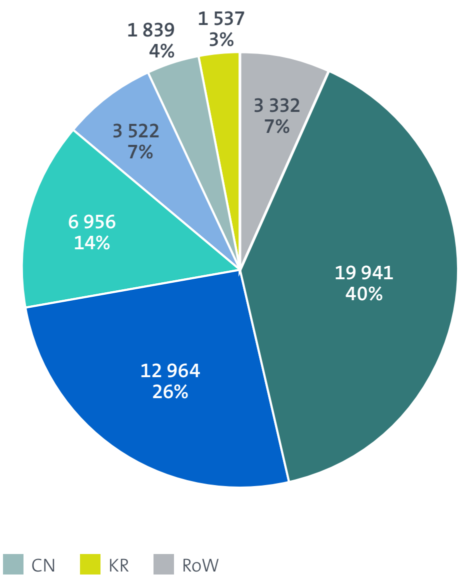
4.1 Global perspective

This chapter presents the geographical distribution of innovation in AM technologies and explores the notable variations among different regions. The installed industrial AM systems are predominantly concentrated in three continents: North America, Europe and the Asia-Pacific region. North America, primarily led by the United States, holds the largest share of installed industrial AM systems, as reported in Chapter 2.3, accounting for almost 35% of the total. The US has been a pioneer in AM innovation, evident not only in its leading share of AM installations, but also in its international patent activities. Between 2001 and 2020, the US contributed nearly 20 000 IPFs, representing 40% of all inventive activity in AM (see Figure 17). This remarkable figure exceeds its share in demand for AM systems, highlighting the US as a driving force in AM innovation.

In comparison, EU applicants contributed around 13 000 IPFs, accounting for 26% of the total IPFs in AM. When combined with other EPC countries, Europe's share increases to 33%, representing one in three IPFs in AM innovation. This share is even higher than Europe's demand for AM installations, which amounted to 31%, indicating a strong commitment to AM technology.

Figure 17

Origin of IPFs in AM technologies, 2001–2020



Source: EPO

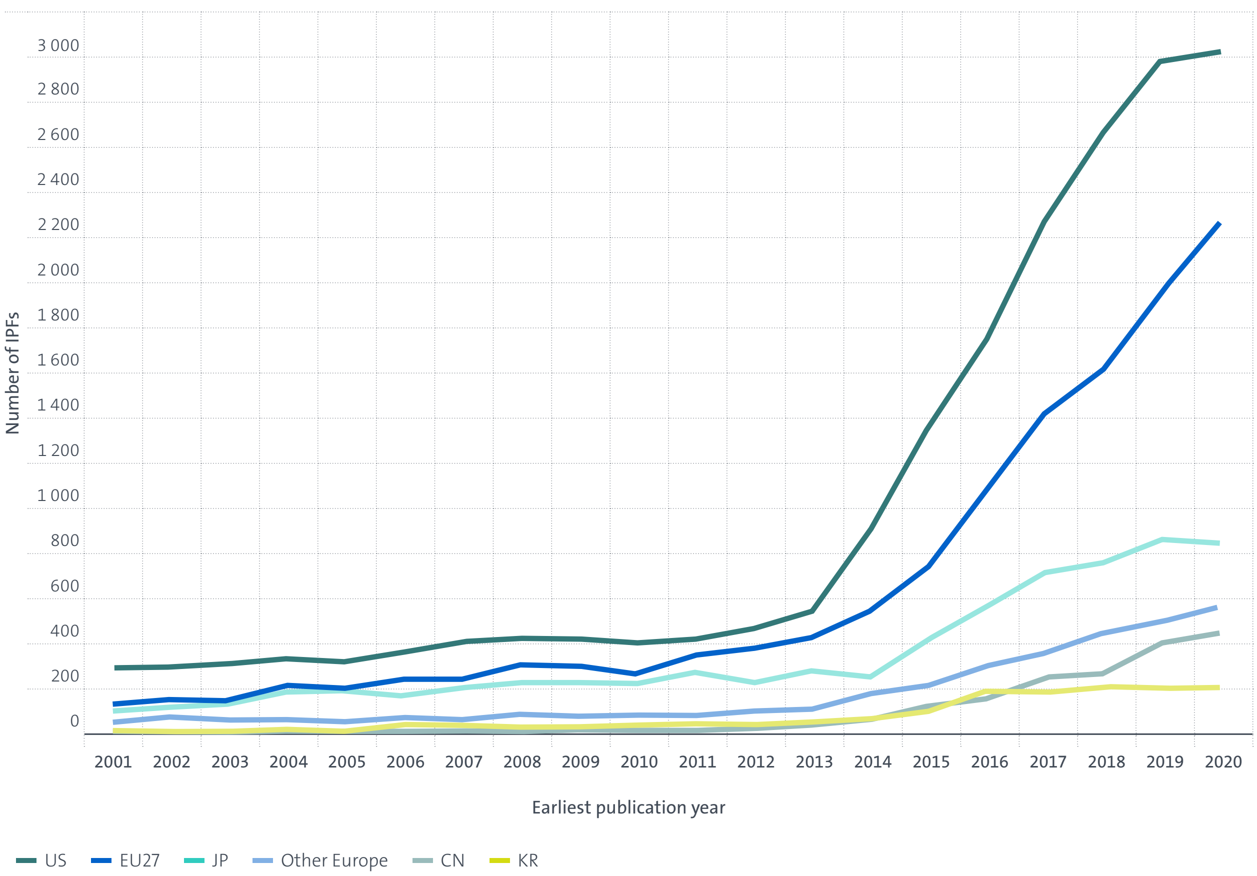
As can be observed in Figure 18, the US and the EU have emerged as leaders across all AM technology sectors. Since 2013, the number of US IPFs has experienced a substantial increase, jumping from 542 in 2013 to over 3 000 IPFs in 2020. Similarly, the EU's contribution grew from 427 IPFs to almost 2 300 IPFs over the same period, showcasing their significant advancements in AM innovation.

In contrast, Asian countries displayed less dynamic growth trajectories in AM innovation. Japan has a relatively modest contribution to AM innovation, with Japanese applicants accounting for almost 7 000 IPFs between 2001 and 2020, equivalent to 14% of the total. Japanese contribution experienced growth from less than 300 IPFs in 2014 to 860 IPFs in 2019, but witnessed a decline in 2020.

Interestingly, P.R. China and R. Korea have relatively low contributions to AM innovation compared to their involvement in other digital transformation technologies, such as cloud computing, AI or advanced communication systems (see EPO, 2020 (a)). P.R. China's contribution to AM IPFs stands at 4%, while R. Korea's is at 3%. These figures are considerably lower than their shares in installed industrial AM systems . More recently, IPFs from R. Korea have stagnated at around 200 since 2016, while China has shown continuous growth, albeit from a relatively lower base. However, with fewer than 450 IPFs in 2020, China still lags behind the US and Europe in terms of AM innovation.

Figure 18

Trends in IPFs in AM technologies by country of origin, 2001–2020



Source: EPO

Although the US and the EU are leading across all AM technology sectors, there are nevertheless some notable differences (see Figures 19-21). Such variations highlight the diverse strengths and areas for improvement among different regions and countries, presenting opportunities for collaboration and further advancements in AM technologies.

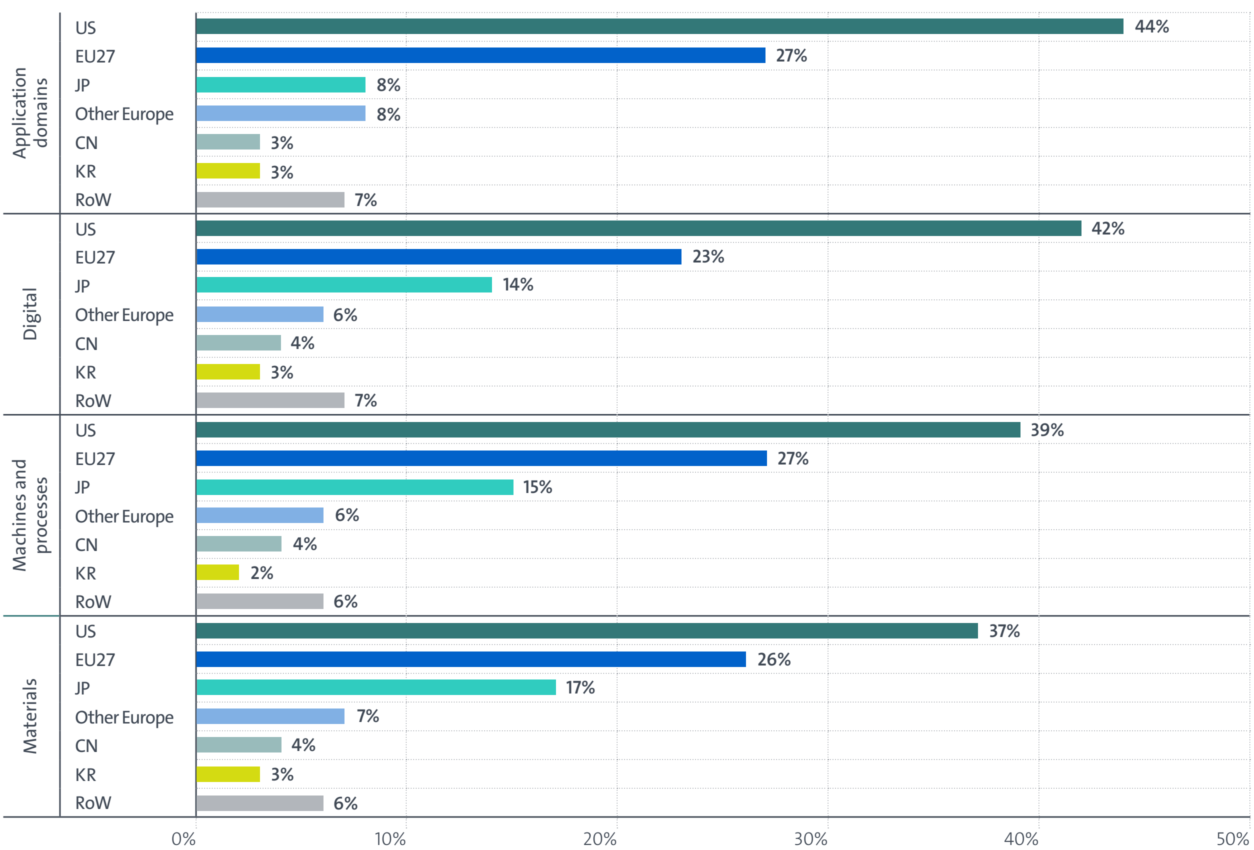
The variation in AM innovation becomes evident when considering the application domains (Figure 20). The US leads in application domains such as energy, transportation, and health and medical, with 53%, 49%, and 47% of all IPFs respectively. However, the US exhibits relative weaknesses in food (29%) and construction (31%) domains. Conversely, the EU excels in the construction domain, with a 37% share, while lagging behind in health and medical, with only 22%. In other application domains, the EU's share ranges between 25% and 30%. Japanese applicants excel in electronics (19%) and machine tooling (12%), whereas their shares remain around 5% in most other domains.

In terms of materials (see Figure 21), Japan is strongest in polymers, accounting for a 17% share, where they are on par with EU applicants. In contrast, materials, with 37%, is the weakest technology sector for US applicants (see Figure 19). However, biomaterials is a notable exception where US applicants clearly dominate with 49% of all IPFs. The EU occupies the largest shares in cement, concrete, or artificial stones, as well as in ceramics and glass, with 39% each. The EU is weakest in biomaterials, with a share of 20%.

When examining the digital technology sector, the EU exhibits a relatively lower share, accounting for only 23% of all IPFs. In contrast, the US leads in this sector, contributing 42% of all IPFs, while Japan holds a 14% share. In machines and processes, the EU has a share of 27%, while the US's share amounts to 39%.

Figure 19

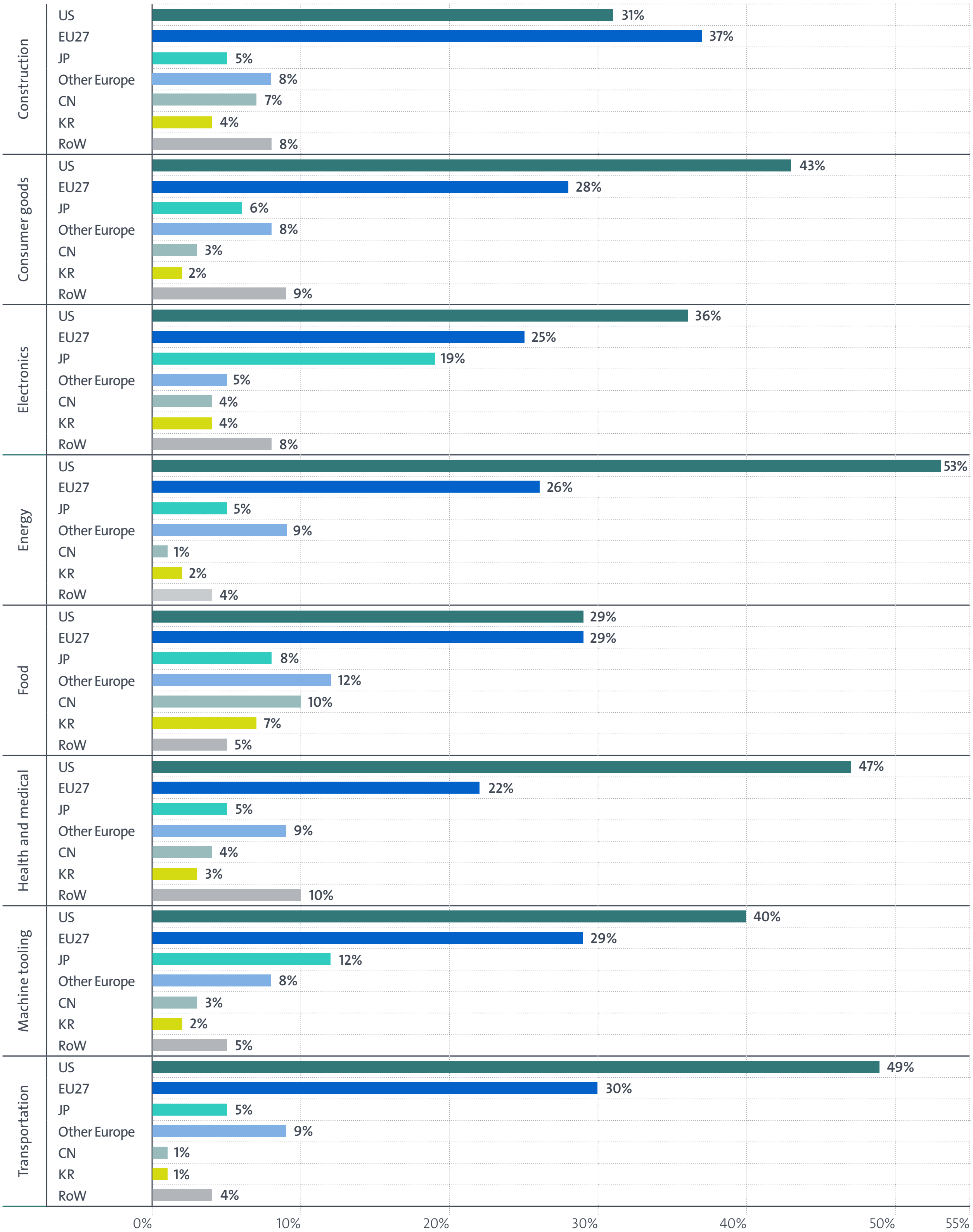
Share of IPFs in AM technology sectors by country of origin, 2001–2020



Source: EPO

Figure 20

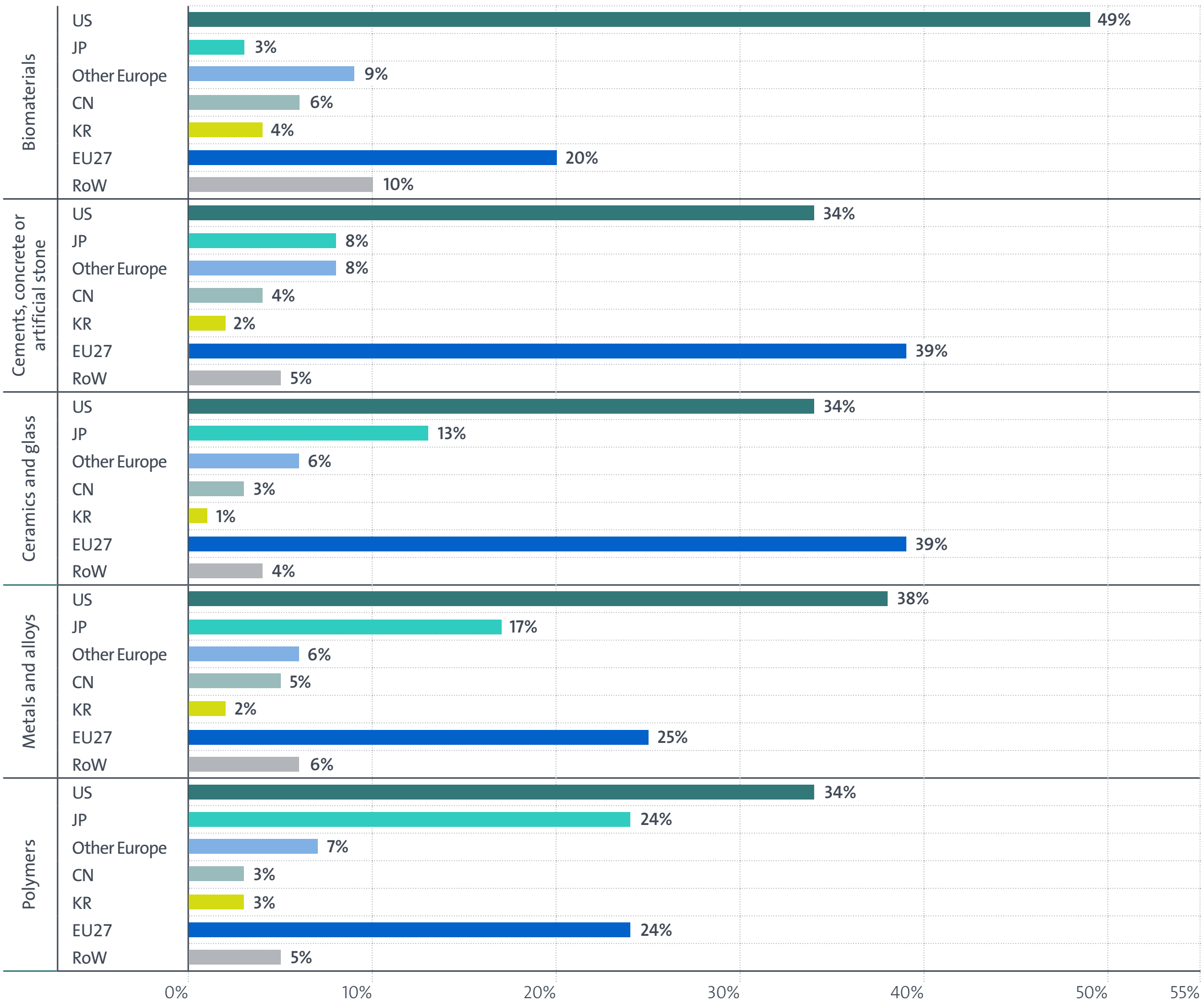
Share of IPFs in AM application domains by country of origin, 2001–2020



Source: EPO

Figure 21

Share of IPFs in AM materials by country of origin, 2001–2020



Source: EPO

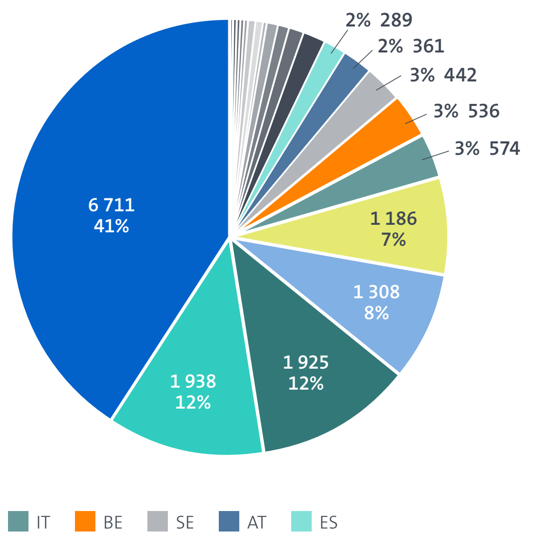
4.2 European perspective

This chapter delves into a more detailed analysis of the member states of the European Patent Office, consisting of 39 European countries, including the 27 member states of the EU. The findings shed light on the contributions and strengths of these countries in AM innovation.

Germany emerges as the clear leader among European countries, with a remarkable contribution of over 6 700 IPFs between 2001 and 2020, representing 41% of all AM inventive activity in Europe (see Figure 22). Notably, Germany's contributions have experienced strong growth since 2013, with the number of IPFs increasing from 213 to over 1 100 in 2020 (see Figure 23). Following Germany, France and the United Kingdom come next, each with a 12% share of IPFs. However, in recent years, France has emerged as the clear second, with 431 IPFs in 2020, while the number of IPFs from the UK has stagnated at around 280 since 2018. Switzerland and the Netherlands also make notable contributions to AM innovation, with over 200 IPFs in 2020. Switzerland contributed 1 308 IPFs between 2001 and 2020, while the Netherlands had 1 186 IPFs during the same period. These developments reflect the dynamic nature of AM innovation within different European countries.

Figure 22

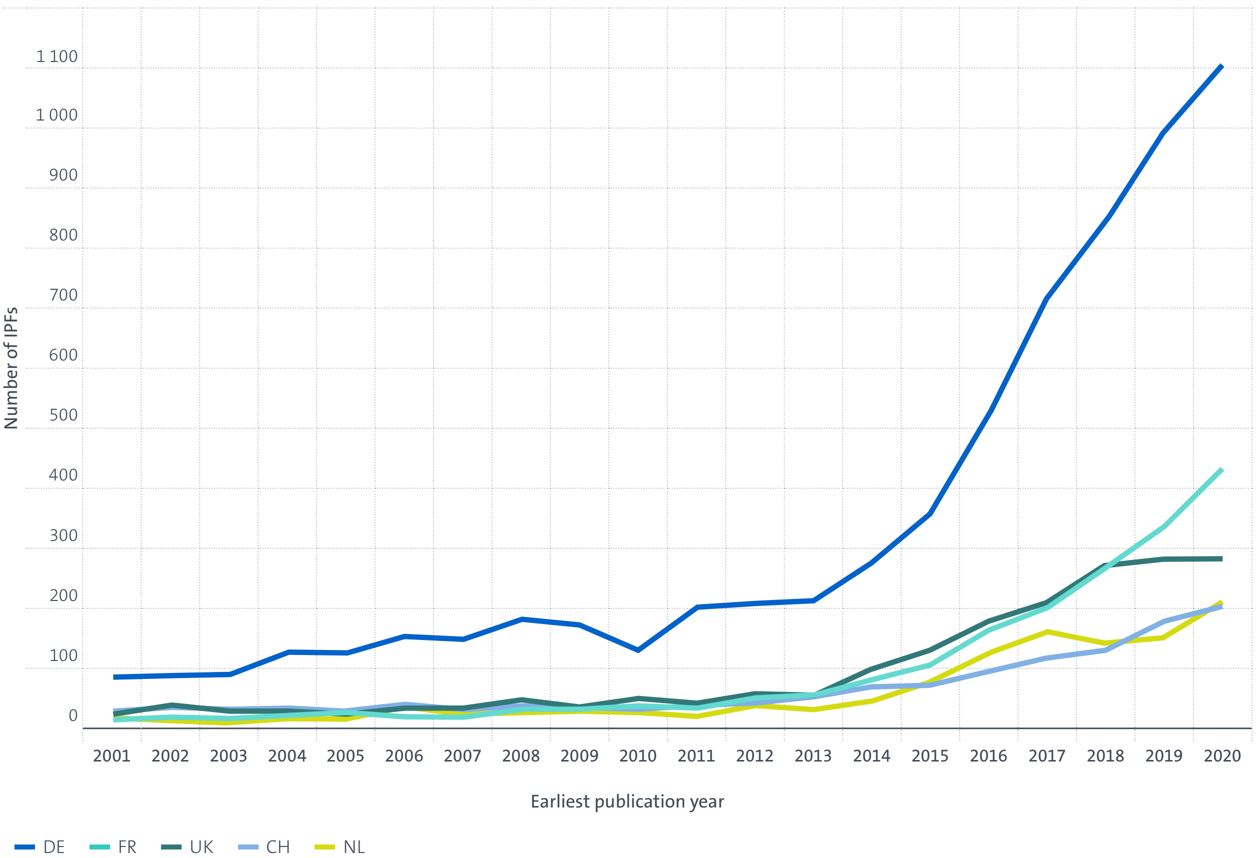
Origins of IPFs in AM technologies by EPO member state, 2001–2020



Source: EPO

Figure 23

Trends in IPFs in AM technologies by top EPO member state, 2001–2020

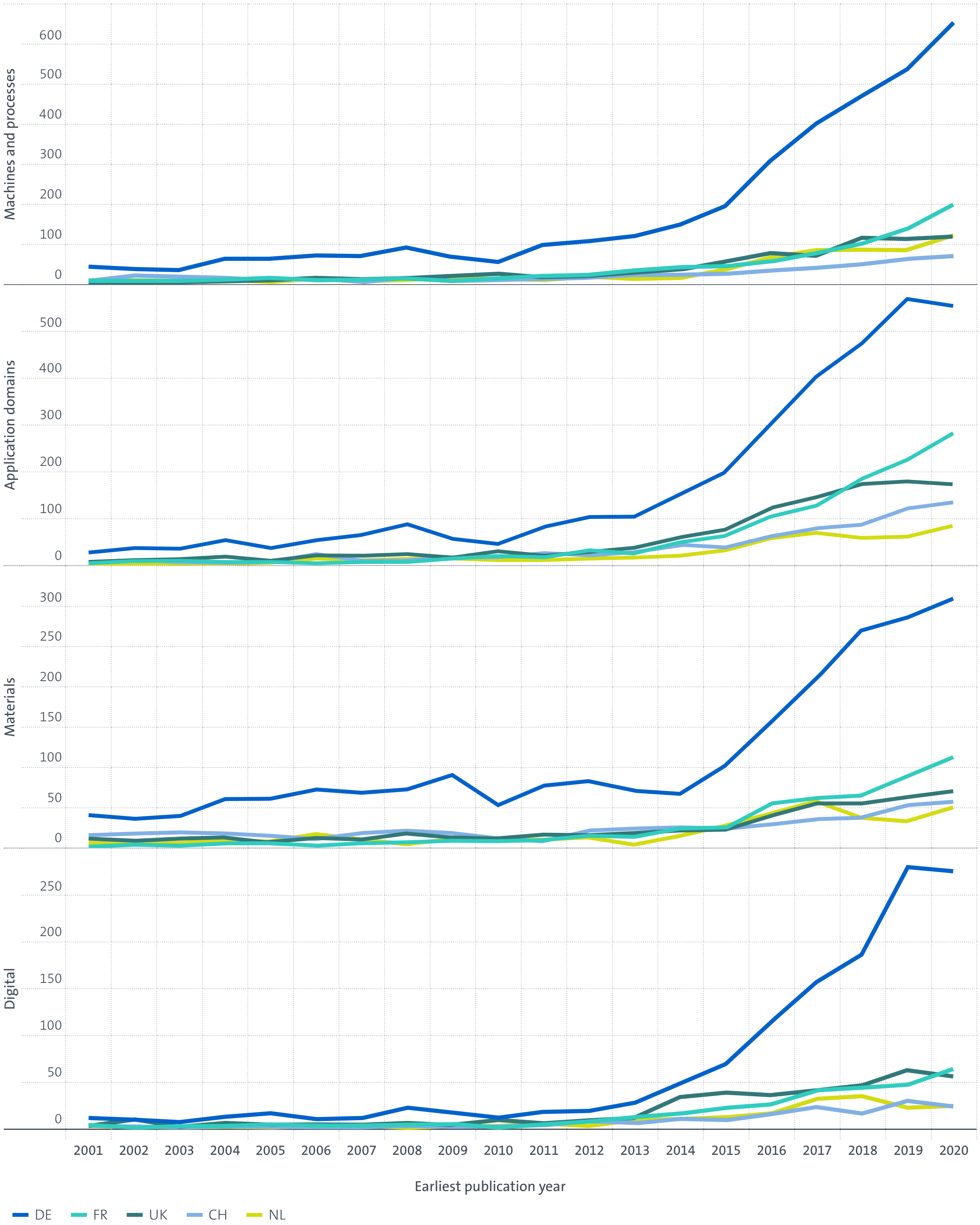


Source: EPO

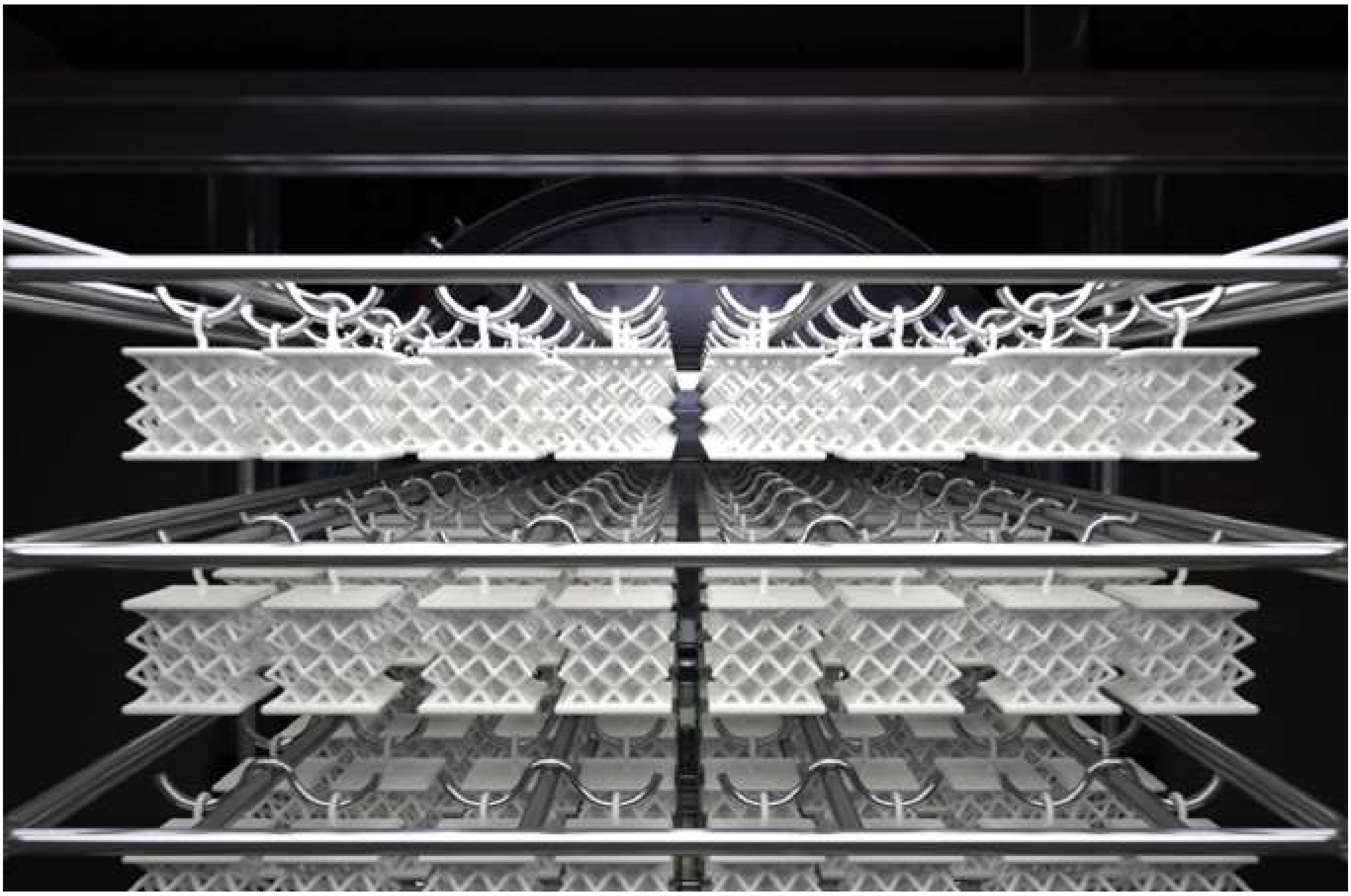
The contributions of the top five European countries and their involvement across different AM technology sectors are presented in Figures 23 and 24. Germany emerges as the leading force in all sectors, with France as the clear second, albeit at a distance. France closely follows Germany in machines and processes, application domains, and materials. In digital, France is on par with the United Kingdom. A closer look at the application domains reveals that while Germany contributes the most to all eight fields, it clearly dominates in machine tooling, consumer goods, transportation, and electronics. In health and medical, notable contributions come from France and Switzerland. In the construction domain, France emerges as a real contender, while in energy, both France and the UK applicants contribute significantly. Additionally, applicants from Switzerland have a relatively high share in the food domain.

Figure 24

IPFs in AM technology sectors by EPO member state, 2001–2020



Source: EPO



DyeMansion Powerfuse

Case study: DyeMansion

Company:	DyeMansion GmbH
Locations:	Germany, US
Founded:	2015
No. of employees:	95
Products:	End-to-end post processing technology for industrial 3D printing

"Keep asking the question: do we have enough traction for the next round? Earlier funding means more resources in R&D and IP activities, which can increase your technology leadership."
Philipp Kramer, CTO and co-founder, DyeMansion

The competitive advantage of early IP

DyeMansion builds technology for the factory of the future – using industrial 3D printing. The Munich-based company offers integrated post-processing solutions for 3D-printed plastics. Their so called "print-to-product workflow" combines industry-leading hardware tech with the widest range of finishes and colours on the market. The end-to-end solutions turns raw 3D-printed parts into high-value end-use products ranging from customised eyewear to tailor-made medical orthotics. With over 900 installed systems and 400 customers in 40 countries, DyeMansion is the clear market leader in their integrated post-processing for 3D-printed plastics category. The company was established in Munich in 2015 and has expanded its operations to Austin, Texas. However, the patented solution developed by the co-founders Felix Ewald and Philipp Kramer gave them a competitive advantage when the AM sector began to evolve.

Wisdom and timing

Kramer and Ewald had been planning an AM start-up to produce customised smartphone cases and developed a novel process for surfacing and colouring. Being their first business angel and boasting extensive IP experience, Kramer's father convinced the young founder duo to seek patent protection and even contributed towards the costs early on. In 2014, they filed their first two patent applications and soon became aware that their invention could be used for far more than smartphone covers.

Additive manufacturing in the 1990s was largely centred on prototyping, with key patents held by relatively few big players. From 2010 onwards, the sector began to rapidly change, and new competitors emerged. This is when Kramer and Ewald decided to pivot from smartphones to developing industrial post-processing technology for 3D printing. They already had a key bargaining chip for investment negotiations: their patents.

In their first seed funding round in 2015, the newly formed DyeMansion raised €1 million. They obtained a further €7 million in 2018 and €12 million in series B funding in 2020. The company looks for backers that are exclusively B2B technology investors focussed on long-term growth. These investors tend to value IP and a proof of technology. DyeMansion's early patents proved valuable assets that enabled them to secure funding for research and development and strengthen their IP cover.

Learning and growing

"You don't really have to develop the complete technology in order to patent it, and those patents might be quite valuable when defending your portfolio."

While Kramer's father provided the impetus for their early patents, DyeMansion has since built a robust IP portfolio. Today, they protect their technology and processes with patents, keep certain colour recipes as trade secrets and use registered trade marks to safeguard their brand.

Their experience with smartphone covers proved formative and the company is now filing for broad patent protection. They are running fast feasibility studies on potential inventions and base their decision to file an application on these rapid studies. In some instances, an innovation may not be feasible in their current product line-up due to, for example, the size and output of an AM factory. However, having patents in place enables DyeMansion to rapidly adapt if productivity requirements increase within the next few years. While the company does not actively license these inventions, the IP gives them flexibility to negotiate an agreement should their strategy change.

5. The applicants behind AM innovation

5.1 Top applicants

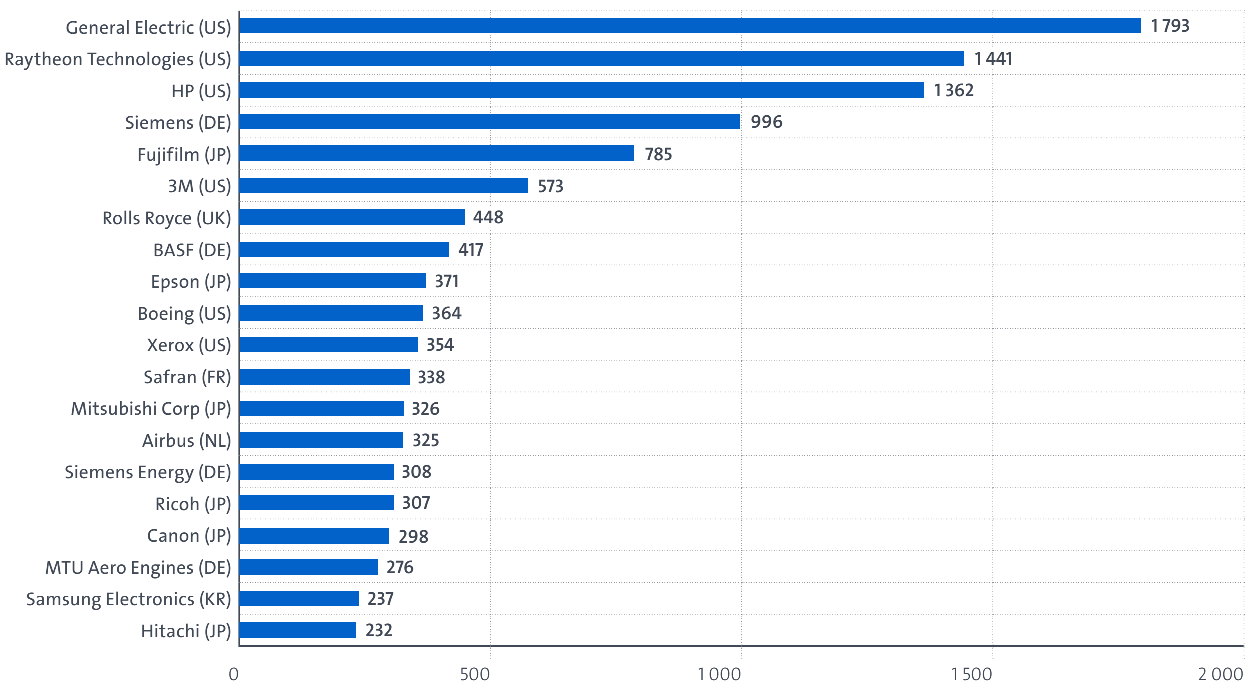
When examining the largest contributors to innovation in additive manufacturing, the applicants of IPFs provide valuable insights into the key players in this field. Between 2001 and 2020, three US companies stood out by generating over 1 000 IPFs each (see Figure 25). General Electric leads the pack with almost 1 800 IPFs, followed by Raytheon Technologies with 1 441 IPFs and HP with 1 362 IPFs. Notably, six US companies are among the top 20 contributors. However, Europe also boasts seven companies in the top 20, including four from Germany, and one each from the UK, France, and the Netherlands. Siemens, with nearly 1 000 IPFs, emerges as the largest European contributor, closely followed by Rolls Royce with just under 500 IPFs. Safran, with 338 IPFs is the most important French applicant. Interestingly, Fraunhofer Gesellschaft, is the largest public research organisation, placed 21st, showcasing its significant impact with 221 IPFs.

Furthermore, six Japanese companies complement the list, with Fujifilm leading the pack with 785 IPFs. Notably, Fujifilm held the largest IPF portfolio in AM technologies until 2013 before companies like Siemens, General Electric, HP and Raytheon Technologies began building their AM patent portfolios (see Figure 26).

Although the list of top applicants is dominated by large, international companies from various industry sectors, it also includes several established 3D printing firms and emerging start-ups. Among these are notable companies such as EOS from Germany with 200 IPFs, and Materialise from Belgium and Stratasys from Israel, both boasting over 100 IPFs. These examples illustrate the rich and diverse landscape of contributors that are actively shaping AM innovation, demonstrating that the field is not solely influenced by the industry giants but also enriched by specialised 3D printing companies.

Figure 25

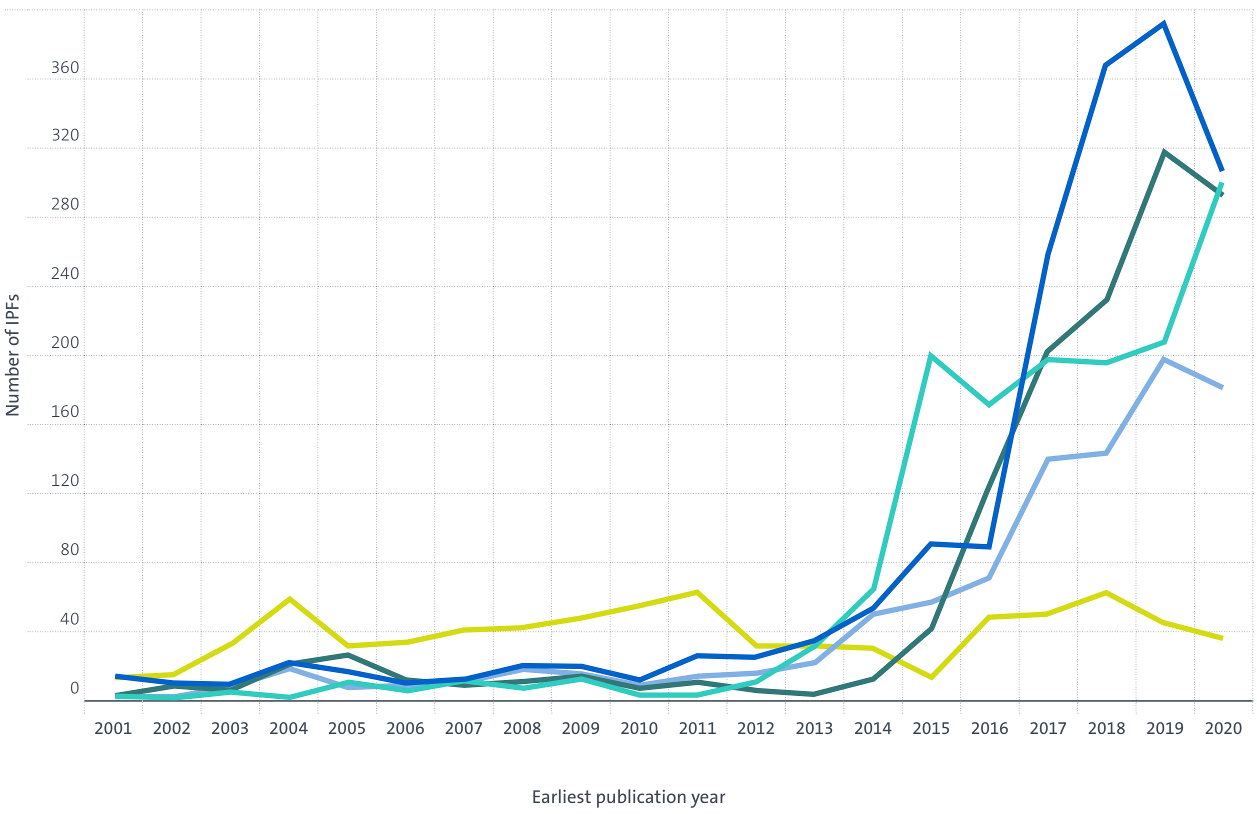
Top 20 applicants in AM technologies, 2001–2020



Source: EPO

Figure 26

Patenting trends of top applicants in AM technologies, 2001–2020



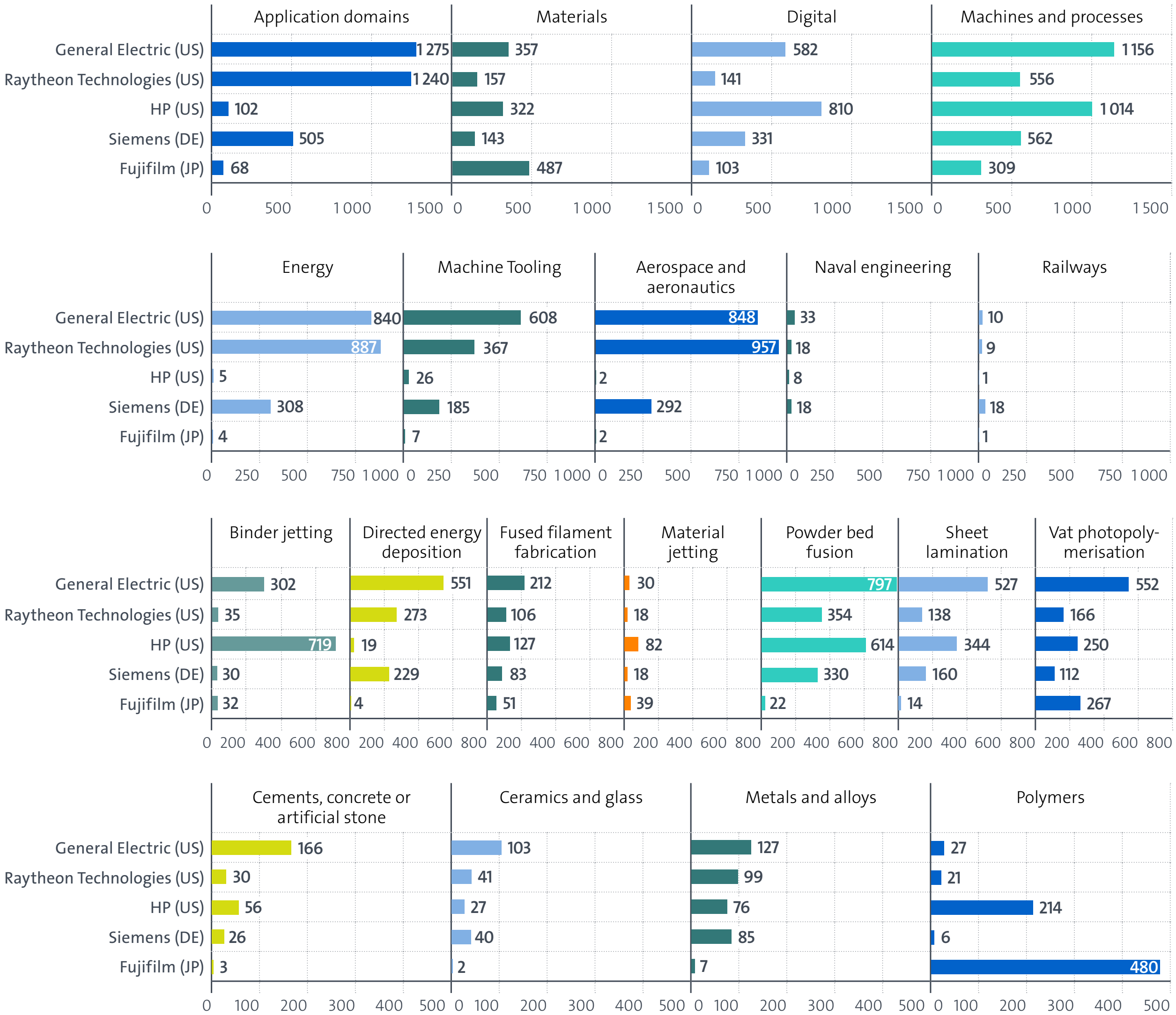
Source: EPO

Analysing the focus of these companies' patent portfolios, as shown in Figure 27, General Electric (GE), a renowned American multinational conglomerate with a rich history in manufacturing and technology, has been at the forefront of AM advancements. The company's substantial patent portfolio reflects its commitment to application domains like aerospace and aeronautics, naval engineering, energy, and machine tooling. GE's expertise and investments in AM have resulted in notable achievements, including the production of 3D-printed jet engine components and advancements in metal AM technologies. It is also the technology leader in many AM process categories. The portfolio of Raytheon Technologies, a major US aerospace and defence company, exhibits similar traits, especially in application domains. Raytheon Technologies has been actively exploring AM applications in aeronautics and aerospace, including the production of lightweight components, intricate geometries and optimised designs, which may also be useful for the energy sector.

HP, which is globally recognised for its contributions to the field of printing and imaging technologies, is a leader in AM machines and processes, and digital technologies. HP has focused on enhancing AM's speed, cost-effectiveness and scalability. In recent years, HP has made significant strides in binder jetting with its Multi Jet Fusion (MJF) technology. The company's substantial annual IPF count in 2019 and 2020 reached around 300. As a major contributor from Europe, Siemens has embraced AM as a transformative technology. With a balanced IPF portfolio across all four AM technology sectors, Siemens has demonstrated a commitment to advancing AM applications in various domains. The company's expertise spans AM machines and processes to materials and digital solutions; noteworthy is its contribution of 18 IPFs to AM for railways. Fujifilm's clear focus is in creating AM solutions for polymers using vat photopolymerisation.

Figure 27

Technology profiles of top five applicants in AM technologies, 2001–2020



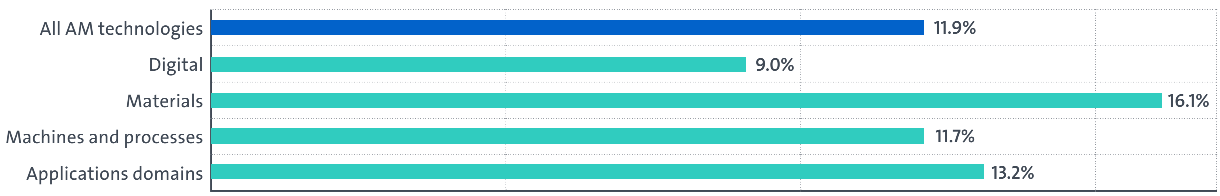
Source: EPO

5.2 The role of universities and PROs

Universities and public research organisations play a pivotal role in driving innovation, not only in additive manufacturing. For example, 7% of all patent applications filed with the EPO in 2022 by European applicants (EPO member states) were filed by universities and public research organisations.[16] Universities and PROs serve as hubs of knowledge creation and dissemination, fostering a collaborative environment where researchers, scientists and students, often in collaboration with private companies, can explore cutting-edge ideas and technologies. Universities and PROs often receive government funding, enabling them to conduct long-term, high-risk research, which private companies may shy away from due to potential financial uncertainties. Their commitment to fundamental research lays the foundation for breakthroughs, leading to significant advancements in AM technology. Lastly, universities and PROs nurture the next generation of skilled professionals in the field, fostering a knowledgeable workforce that can drive practical implementation and commercialisation of innovative AM solutions. The fact that approximately 12% of IPFs are assigned to a university or PRO as an applicant underscores their significant contributions to advancing AM technologies. Notably, the variation across different AM technology sectors, as shown in Figure 28, further emphasises their importance. While digital AM has the lowest share of 9%, materials, with 16% overall, sees the largest contributions from research institutions. In particular, biomaterials stands out with an impressive 32% share, indicating that universities and PROs are instrumental in driving developments in this area (see Figure 30). Moreover, AM applications in health and medical as well as food benefit greatly from innovation from these institutions, as almost every fourth IPF in these domains originates from university or PRO research (see Figure 29). On the other hand, areas like transportation and consumer goods, with only 4% involvement from research institutions, are more dominated by the private sector.

Figure 28

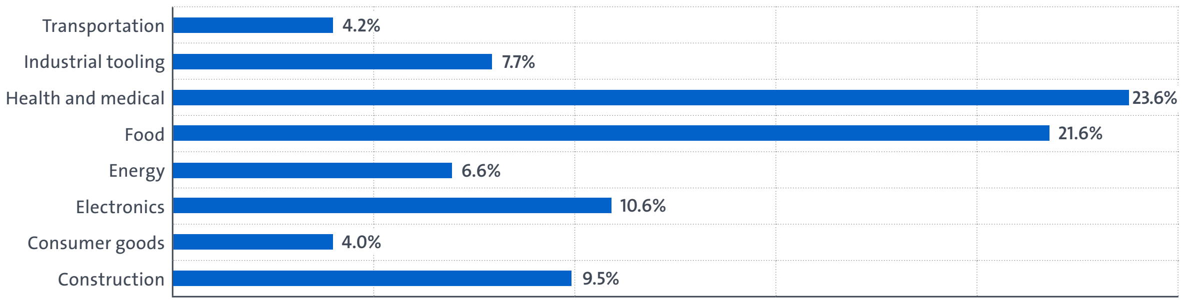
Share of universities and PROs in AM technology sectors, 2001–2020



Source: EPO

Figure 29

Share of universities and PROs in AM application domains, 2001–2020

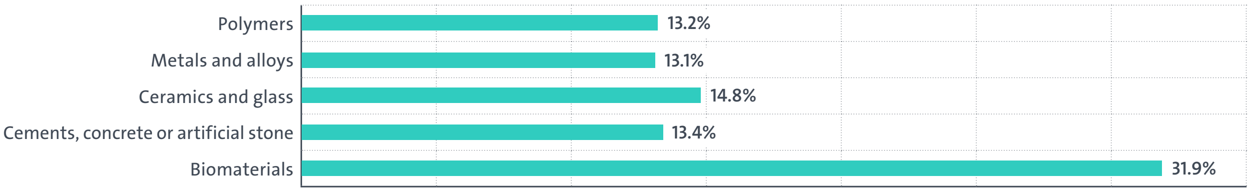


Source: EPO

16 See EPO Patent Index 2022 (https://www.epo.org/about-us/annual-reports-statistics/statistics/2022/statistics/applicants.html).

Figure 30

Share of universities and PROs in AM materials, 2001–2020



Source: EPO

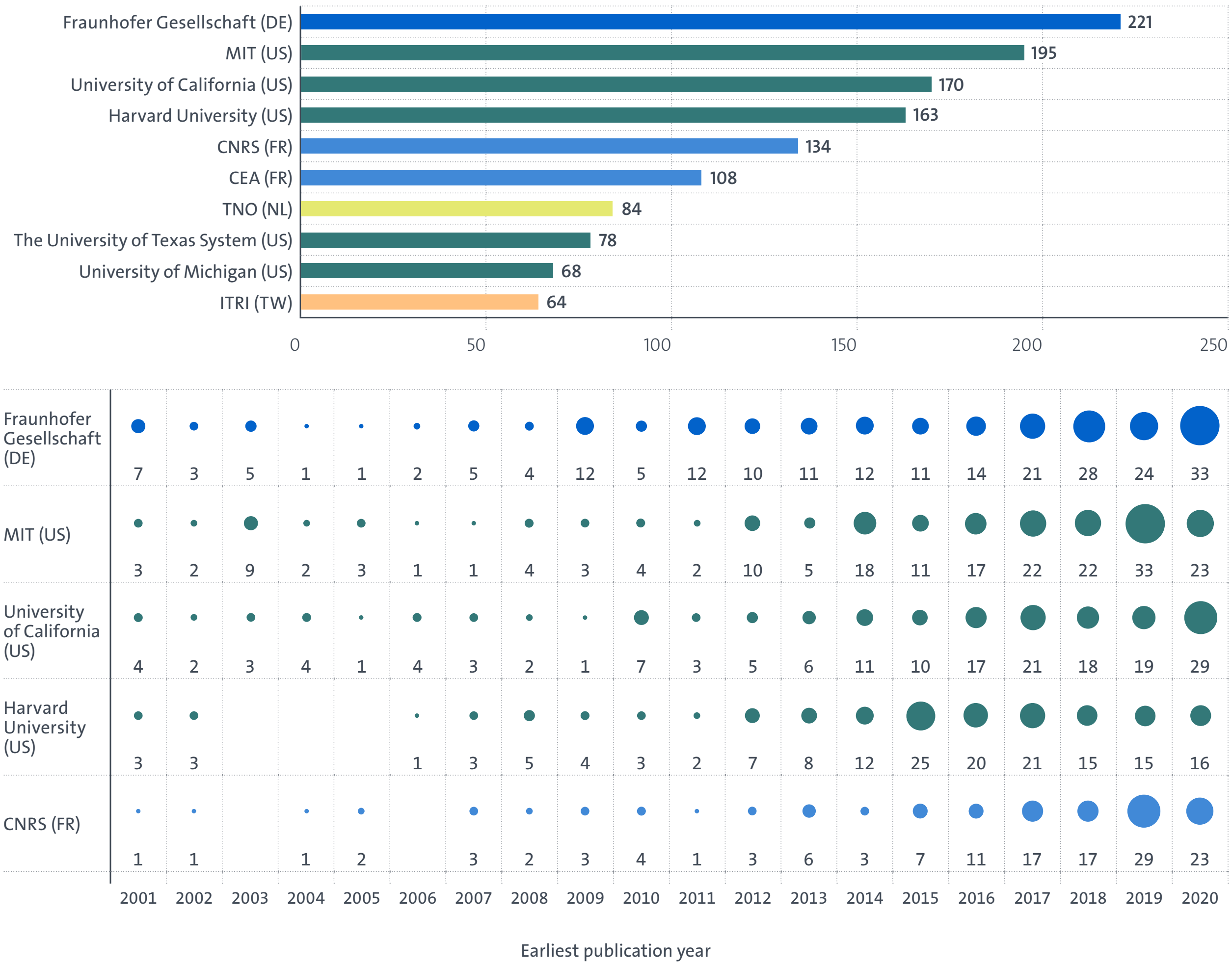
Among the top ten institutions, five are located in the US, showcasing the nation's prominence in AM research (see Figure 31). Notably, MIT ranks second with 195 IPFs from 2001 to 2020, followed by the University of California in third place with 170 IPFs and Harvard University in fourth with 163 IPFs. However, the clear leader among them is the German institution Fraunhofer Gesellschaft, with an impressive 221 IPFs. Apart from the US and Germany, two French institutions (CNRS and CEA) and the Dutch institute TNO represent Europe, while the Taiwanese ITRI stands as the sole Asian organisation among the top performers.

The top five institutions expended their AM patent portfolios over the last decade, each reaching double digits in IPFs per year. Interestingly, their contributions to the AM technology sectors of application domains and materials are quite similar, except for CNRS, which exhibits a stronger focus on materials (see Figure 31). However, a closer examination of their patent data reveals unique research emphases within those sectors. The US institutions stand out in biomaterials, while Fraunhofer Gesellschaft and CNRS excel in ceramics and glass. Moreover, Fraunhofer's strength lies in metals and alloys, while CNRS leads in cements, concrete, and artificial stone. On the other hand, all institutions demonstrate a substantial interest in polymers.

Significant differences are also apparent across application domains. The US institutions' emphasis on biomaterials aligns with their extensive portfolios in 3D printing of organs and artificial tissue. Additionally, MIT and Harvard have numerous IPFs related to 3D printing of drugs and pharmaceuticals, while the University of California shines in dental applications. Fraunhofer Gesellschaft is emerging as a powerhouse in machine tooling, with 49 IPFs, and also displays strength in energy-related applications. Furthermore, the analysis indicates specific AM processes where institutions contribute significantly. Fraunhofer Gesellschaft plays a prominent role in the development of AM processes like directed energy deposition and powder bed fusion, whereas MIT focuses more on vat photopolymerisation and fused filament fabrication.

Figure 31

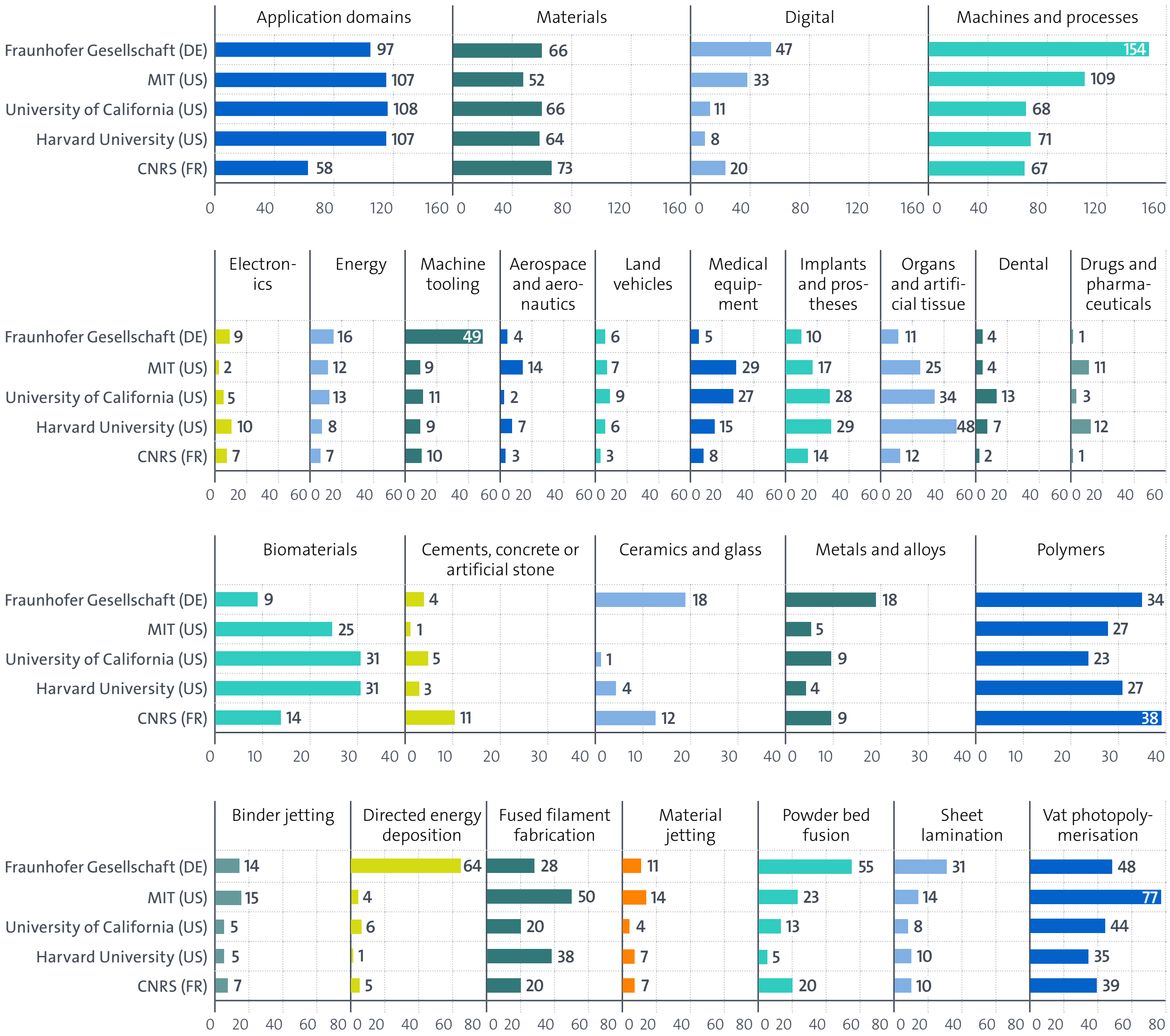
Top research institution in AM technologies, 2001 – 2020



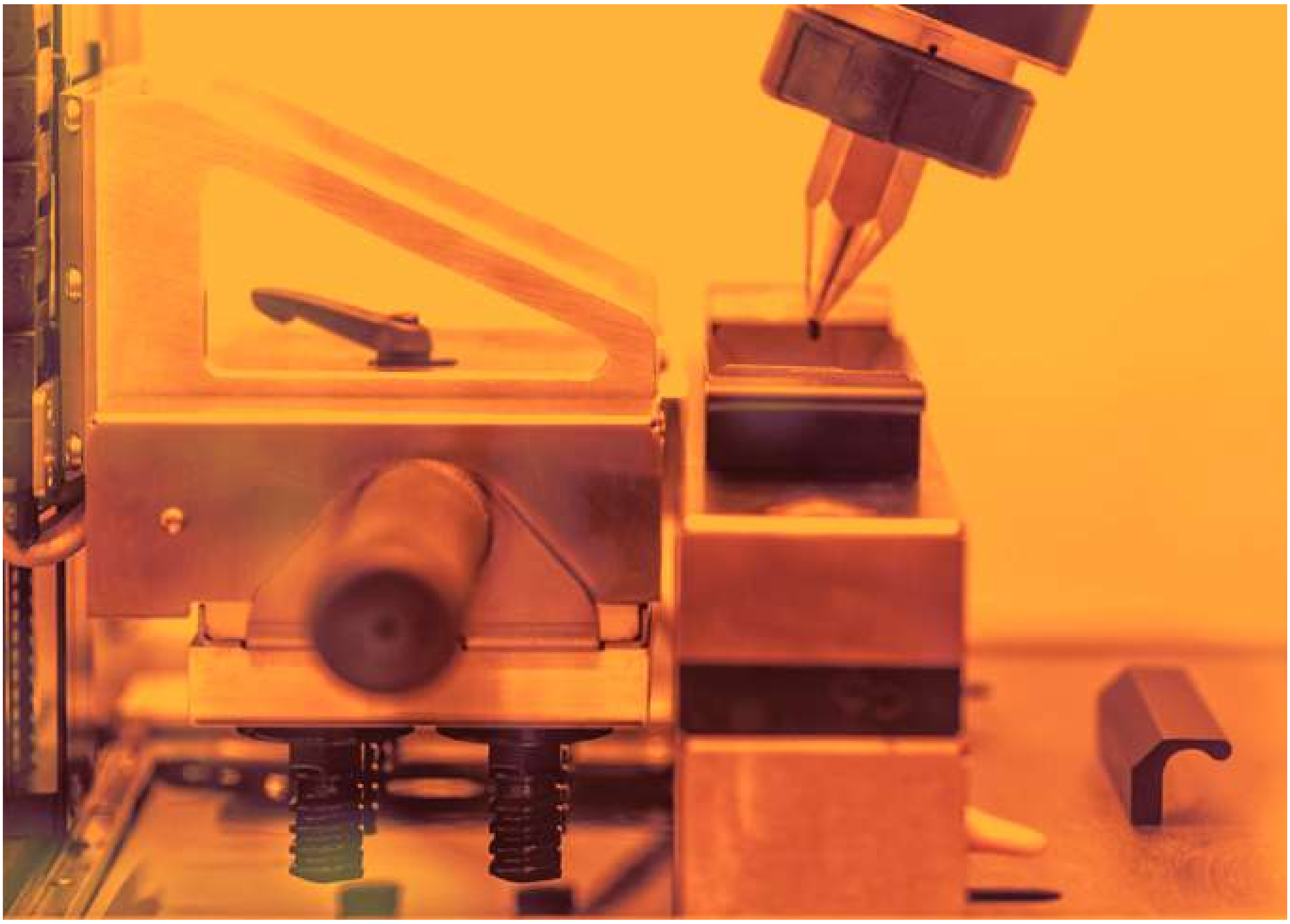
Source: EPO

Figure 32

AM technology profiles of top five research institutions, 2001-2020



Source: EPO



Cubicure's additive manufacturing process Hot Lithography

Case study: CUBICURE

Company: Cubicure GmbH
Locations: Austria
Founded: 2015
No. of employees: 35
Products: AM machines and high-performance polymers for industrial applications

"In the long run, IP is very relevant, but it might be overlooked in the first year - that should be avoided."
Jürgen Stampfl, CEO, Chief Science Officer and co-founder, Cubicure

Securing the long-term

Vienna-based Cubicure[17] develops, produces and distributes materials, equipment and processes for industrial AM. The company was established in 2015 as part of a long-term technology transfer strategy which saw the Technical University of Vienna partner with global dental company Ivoclar. This industry-academia partnership enabled Cubicure to strengthen its patent portfolio, which became crucial in drawing early investors and negotiating strategic research projects with industrial partners

The origin of innovation

In the early 1990s, AM technologies were focussed on producing prototypes for plastic and metal objects with specific geometrical shapes. Professor Jürgen Stampfl at TU Vienna saw the potential for AM to be used with ceramic materials; as his research progressed, he formed an interdisciplinary team to develop new materials and machines. However, the team needed funding and co-operation partners to help take their work from the lab to market.

Ivoclar became interested in the university's work and in 2007 established a partnership that is on-going to this day. The Liechtenstein-based company agreed to fund R&D projects not covered by public grants. They also offered a share of revenue if Ivoclar commercialised the patentable inventions. In return, TU Vienna agreed to provide third-party income if the university licensed the technology in non-dental areas.

The university's technology transfer office (TTO) initially found that the invention needed more tangible data and further research to obtain the strongest possible patent protection. The partners decided to jointly develop the IP and the first patent application was filed in 2008.

Symbiosis: leveraging the partnership agreement

"If the company has IP, background in the field and talented people, it helps for the initial valuation of the start-up, meaning that it's easier to get money, but also to get money without giving away the whole company."

Since its inception, the Ivoclar-TU Vienna partnership has led to the formation of several spin-offs in the AM field, with patents playing a crucial role in getting each off the ground. Lithoz[18], the first of these, was established in 2011 and focused on AM technologies in ceramics. Jürgen Stampfl and Robert Gmeiner, a PhD student, realised that the technology might work for other materials.

They formed Cubicure and negotiated a licence agreement with TU Vienna. Their agreement covered patent families that were not licensed to Lithoz and some that were jointly developed with Ivoclar. However, the licence targeted the production of non-ceramic materials and related AM machines, ensuring that the newly formed Cubicure would not directly compete with Lithoz and Ivoclar.

With a patent portfolio in place from an early stage, Cubicure has been able to secure funding and collaborate on a broad range of research projects. These include an EU Horizon 2020 project on hot lithography, which aimed to develop a cost-effective AM polymer solution for spare parts manufacturing. The EU-funded initiative helped both Cubicure and its project partner to further optimise their products and demonstrate the effectiveness of their technologies.

In addition to being patent licence partners, Cubicure, Lithoz and TU Vienna collaborate on research and development projects. This type of collaboration is often attractive to public funding agencies, who assist with financing for additional PhD students, research material and scaling projects beyond the initial investment. These elements – steady financing and talented researchers – are crucial to the long-term success of industry-academia partnerships. For Cubicure, they have helped the spin-off to grow to a staff of 35 employees and sell their systems internationally with an export rate above 90%.

17 See EPO SME case study CUBICURE: https://link.epo.org/elearning/technology_transfer_case_study_cubicure.pdf

18 See EPO technology transfer case study LITHOZ: https://documents.epo.org/projects/babylon/eponet.nsf/0/BBB2A8DEA3BD92A6C125819B0032D6F2/$File/sme_case_study_lithoz_en.pdf

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