AUTONOMIK
INDUSTRIE 4.0

Additive manufacturing methods – state of development, market prospects for industrial use and ICT-specific challenges in research and development

A study within the scope of scientific assistance for the AUTONOMICS for Industry 4.0 technology programme of the Federal Ministry for Economic Affairs and Energy

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Contents

Illustrations

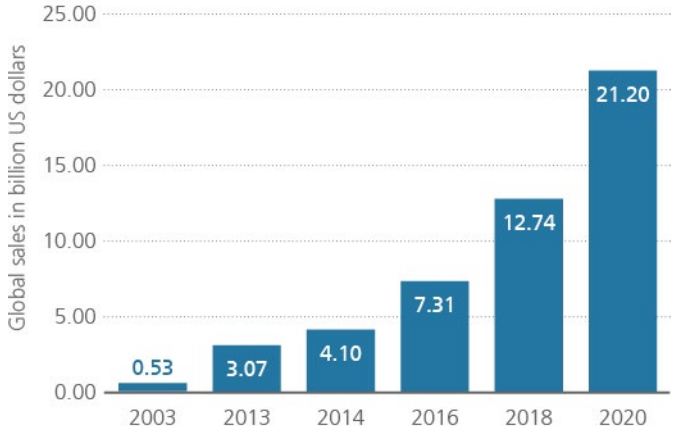
Management Summary

Additive manufacturing (AM) methods, often also collectively referred to as 3D printing, are expected to play an important role as a key technology for the future, especially in conjunction with Industry 4.0 and increasingly individualised production. Unlike conventional machining processes – turning, milling, casting, forging, etc. – additive manufacturing enables the manufacture of complex geometries and internal structures based on a laminar design. Furthermore, additive processes are extremely attractive for a host of applications thanks to the diversity of the materials that can be used, such as ceramic, metal, plastic, wax, etc.

Whilst desktop manufacturing by end users and bioprinting are still in their infancy in terms of technological development, additive manufacturing in industrial contexts has already reached an advanced level of maturity. To this effect, the technological maturity of the different processes and their respective applications were analysed within the scope of scientific assistance for the "AUTONOMICS for Industry 4.0" technology programme supported by the Federal Ministry for Economic Affairs and Energy. This study provides an overview of existing surveys and analyses of additive manufacturing and highlights important ICT-specific fields of action outside core technology developments in order to establish additive manufacturing as a key technology of future smart factories.

The market situation

Whilst no reliable market assessments are available for products from additive manufacturing, a very positive trend exists for AM devices. AM devices include, for instance, 3D printers, materials, accessories and software as well as AM-related services which are used in the manufacture of AM products. Global sales of these products grew almost eightfold between 2003 and 2014, with further exponential growth expected in the coming years. In 2010, German companies recorded a share of 15 to 20 percent of global sales, corresponding to turnover of around 260 million US dollars. An estimated 1,000 or so German companies are active in the field of AM devices, and 90% of these companies are small and medium-sized enterprises.



Global sales of goods and services in the field of additive manufacturing (own diagram, data from EFI 2015, Wohlers 2015).

The most important additive manufacturing technologies

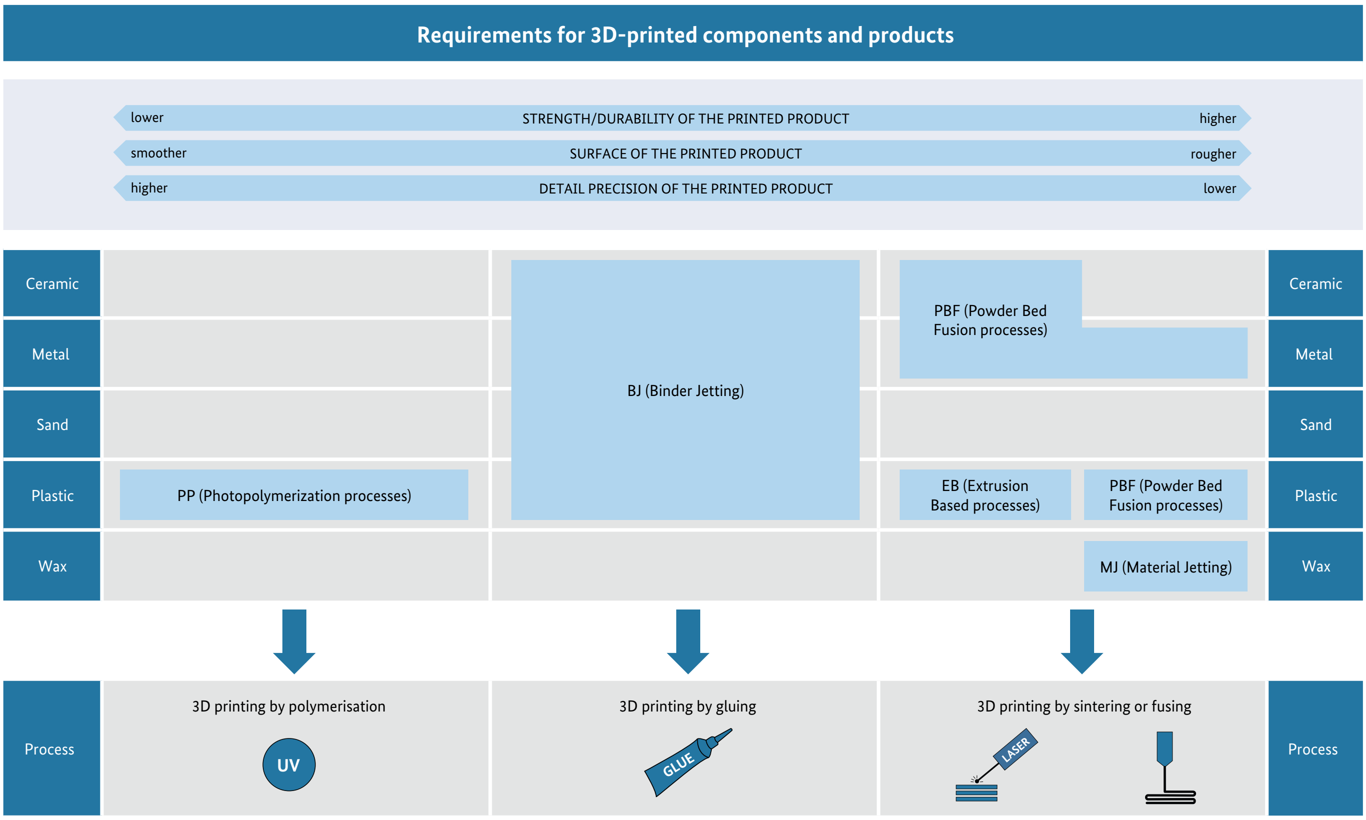
Depending on the materials to be used and the requirements for components and products, different methods of additive manufacturing are available to users. Three of these processes have already reached a high level of technological maturity, offering a wide range of possible applications. Powder-based processes use a thin powder (metal, ceramic, etc.) layer that is applied to a surface and laser-melted to form a defined contour which solidifies after setting. A new powder layer is subsequently applied and the process repeated (PBF process). Extrusion processes use thermoplastic material that is made malleable by a heated nozzle and deposited to form defined geometries (EB process). Photopolymerisation processes use liquid photopolymers which are bonded to a substrate in dot or layer-type patterns so that the polymer solidifies. German companies are leading the field, especially for metal-based PBF processes.

Main fields of application

The main processes described above are already in productive use in various industries for three main applications. Rapid prototyping uses additive methods for the quick manufacture of sometimes even functional prototypes and component samples, rapid tooling is used in tool and mould making, and rapid manufacturing refers to the flexible, quick manufacture of components and series.

State of research and development

The number of technical and scientific articles focusing on additive manufacturing published each year tripled between 2003 and 2012. After scientists in the US and China, scientists from Germany account for the third largest number of scientific publications. The number of patent families applied for shows a similar trend, with the US and Japan as clear leaders. Germany is fourth after China. Research and development projects focusing on material development receive above-average government support at national and European level. Projects that are not directly related to the development of core technology but focus on modelling tools, smart production services as well as sustainability and resource efficiency are currently represented to a far lesser extent, so that there is significant backlog especially at national level.



Requirements for components and products made by additive manufacturing as well as possible processes and materials* (adapted according to additively.com 2015). © iit

* The MJ process can also be applied in conjunction with photopolymers. The objects printed have a high degree of detail and smooth surfaces.

Industry	Powder Bed Fusion processes (PBF)			Extrusion Based processes (EB)			Photopolymerization processes (PP)		
	Prototyping	Tooling	Manufacturing	Prototyping	Tooling	Manufacturing	Prototyping	Tooling	Manufacturing
Automotive industry	✓	✓	✓	✓	✓	✓	✓	×	•
Architecture, furniture industry, design and arts	✓	×	✓	✓	×	✓	✓	×	✓
Electrical engineering and electronics industry	✓	✓	✓	✓	✓	✓	✓	×	×
Film and entertainment industry	✓	×	×	✓	×	✓	✓	×	✓
Aerospace industry	✓	✓	✓	✓	✓	✓	✓	×	×
Medical devices, prosthetics, dental devices, other medical products	✓	✓	✓	✓	✓	✓	✓	✓	×
Food industry	×	×	×	✓	×	•	×	×	×
Defence industry	✓	✓	✓	✓	✓	✓	✓	×	×
Sports equipment industry	✓	✓	✓	✓	×	×	✓	×	×
Toys industry	×	✓	✓	✓	×	✓	✓	×	✓
Textiles and garment industry	✓	×	✓	✓	×	✓	✓	×	×
Science	✓	•	✓	✓	×	×	✓	×	×

✓ Technology is mature/already in productive use   × Technology is not yet mature/not relevant   • Technology is still in the development stage

Explanations:

Rapid **prototyping** uses AM processes for the quick manufacture of sometimes even functional prototypes and sample components.

Rapid **tooling** uses AM processes for tool and mould making with a focus on the timely manufacture of complex tools, for instance, for plastic injection moulding.

Rapid **manufacturing** uses AM processes for the quick, flexible manufacture of parts and series.

Sector-specific fields of application of the most commonly used methods © iit

ICT-specific need for action

Additive manufacturing has its origins in prototype and small-series manufacturing. In order to achieve maximum flexibility, the degree of process automation was deliberately kept low so that processes still require a high level of manual intervention. As a result, the core technologies of additive manufacturing processes are already quite mature. What is now especially needed are ICT-based solutions for the improved use and integration of additive manufacturing processes in order to open up their full potential for future use. In Germany, research and development projects focusing on the relevant key areas of modelling tools, smart production services as well as sustainability and resource efficiency still lag behind projects related to materials. This means that action is required in the following fields:

Modelling tools

- Development of modelling tools and user interfaces for consumers with the highest possible degree of intuitive user interaction
- Development of modelling tools and file formats that enable and/or support the modelling of shapes and behaviours as well as the simulation of component properties
- Development of modelling tools for the machine-interpretable description of objects (morphology, material properties and porosities, component behaviour, component simulation, etc.)

Smart production services and process integration

- Complete automation of additive manufacturing process chains in order to make the processes fit for use as part of automated series production (for instance, adjustment of planning and execution systems, continuous data supply, feeding of printers with print material, removal of printed objects)
- Further development and adaptation of quality assurance tools (for instance, non-destructive testing methods based on ultrasonic and 3D monitoring)
- Automated adjustment of virtually planned and real production processes, so that systems can, for instance, be adapted automatically when deviations occur
- Development of communication standards and tools for integrating additive manufacturing into further production processes and the smart factories of tomorrow

Sustainability and resource efficiency

- Development of concepts and technologies for building 3D printer networks in order to achieve optimum utilisation beyond site boundaries
- Development and adaptation of logistics concepts and technologies that support 3D printer sharing concepts in realtime
- Examination of possible rebound effects and eco-balances of the technologies and processes used as well as their applications

1 Introduction

Additive manufacturing (AM), also called 3D printing by the lay community, is extremely popular today. The Commission of Experts for Research and Innovation (EFI) set up by the German government expects that additive manufacturing will take on an important role as a key technology (EFI 2015). It is also the subject of extensive discussion in society, it records a large number of hits in searches and has a political and normative background.

ASTM, the international standards developing organization, defines additive manufacturing as follows (ASTM 2012): "Additive Manufacturing is a process of joining materials to make objects from three dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. As a new tool in the entrepreneurial toolbox, additive manufacturing systems use computer-aided design models (CAD) and 3D scanning systems for production."

Unlike subtractive (turning, milling) and formative (casting, forging) processes, additive manufacturing enables the manufacture of complex geometries and internal structures based on a laminar design. Furthermore, the diversity of materials (plastic, metal, ceramic, concrete, cells, etc.) that can be used and their implicit properties make additive manufacturing very attractive for a wide range of applications.

Whilst the technology has already reached a high level of maturity for industrial production in many areas, desktop manufacture by consumers and bioprinting are still in a very early stage of technological development (EFI 2015). Table 1 shows industries applying additive manufacturing as well as examples of applications.

Joint standards for additive manufacturing were already introduced as part of co-operation between the ISO and ASTM standards developing organizations (the Appendix, chapter 7.1, p. 26, contains an overview). Specific legal issues of additive manufacturing are being discussed primarily in light of new business models (VDI 2016b). However, the existing legal framework (liability, patent law, etc.) is considered to be sufficient to settle disputes.

Table 1

Application examples of industries using additive manufacturing (adapted according to VDI 2014).

Industry	Application examples
Automotive industry	Water pump wheel (cooling), rear fog light, interior trim http://www.3d-grenzenlos.de/magazin/thema/3d-druck-automobilindustrie
Architecture, furniture industry, design and arts	Model making, bridge construction, building construction and prefabricated building parts, insulation, interior design http://www.3d-grenzenlos.de/magazin/thema/3d-drucker-architektur
Electrical engineering and electronics industry	Development of 3D printing paste, prototypes, for instance, drones http://www.heise.de/newsticker/meldung/Gedruckte-Drohnen-dank-Silbertinte-2582345.html
Film and entertainment industry	Props, scenery, masks, armour, jewellery, sculptures http://www.kubikwerk.de/branchen/film-und-fernsehen/
Aerospace industry	Parts for jet engines, jet gears, components (such as window frames), etc. http://www.3d-grenzenlos.de/magazin/thema/3d-druck-luftfahrt
Medical devices, prosthetics, dental devices, other medical products	Prostheses, hearing aids, dentures, tissue http://www.3d-grenzenlos.de/magazin/thema/medizin-3d-drucker
Food industry	Fruit gum, haute cuisine http://www.3d-grenzenlos.de/magazin/thema/lebensmitteldrucker
Defence industry	Drones, arms (such as warheads), customised uniforms http://www.3d-grenzenlos.de/magazin/thema/3d-drucker-militaer
Sports equipment industry	Customised shoes, bicycle handlebars, snowboards, Paralympics http://www.3d-grenzenlos.de/magazin/thema/3d-drucker-sport/
Toys industry	Printed Lego, cuddle toys http://www.3d-grenzenlos.de/magazin/thema/spielzeug-3d-drucker
Textiles and garment industry	Especially shoes and fashion http://www.3d-grenzenlos.de/magazin/thema/kleidung-3d-drucker/
Science	New materials (including self-assembly), process chain, bioprinting, medical devices, microstructures http://www.3d-grenzenlos.de/magazin/forschung/page/2

2 The market situation

Whilst no reliable estimates are available for global sales of products from additive manufacturing, the EFI study (EFI 2015) summarised the market situation for AM devices and their future development on the basis of results compiled by a market research firm. AM devices include, for instance, 3D printers, material, accessories and software as well as AM-related services which are used in the manufacture of AM products.

Global sales of AM devices increased almost eightfold between 2003 and 2014, and market development forecasts are also good (Fig. 1). In 2010, German companies recorded a share of 15 to 20 percent of global sales of AM devices, corresponding to turnover of around 260 million US dollars. An estimated 1,000 or so German companies are active in the field of AM devices, and 90% of these companies are medium-sized enterprises as defined by the EU. Important German companies are: EOS Electro Optical Systems GmbH, SLM Solutions GmbH, Voxeljet AG, Concept Laser GmbH, Envisiontec GmbH as well as Realizer GmbH. German companies are global leaders in the field of metal-based PBF processes (VDI 2014).

Global[1] annual sales of industrial 3D printers and desktop 3D printers have increased steeply since 2010. Especially sales of desktop[2] 3D printers have increased dramatically since 2011. Whilst the number of industrial 3D printers sold doubled between 2010 and 2014, sales of desktop 3D printers even increased more than twenty times (Fig. 2).

1 The number of 3D printers sold worldwide is based on data from leading system manufacturers. The global statistics of units sold include figures from the US, Canada, Japan, China, Korea, Singapore, Austria, Denmark, the UK, France, Germany, Ireland, Italy, Sweden and Israel (Wohlers 2015).

2 3D printers costing less than 5,000 US dollars were defined as "desktop 3D printers".

Fig. 1

Global sales of goods and services in the field of additive manufacturing (own diagram, data from EFI 2015, Wohlers 2015).

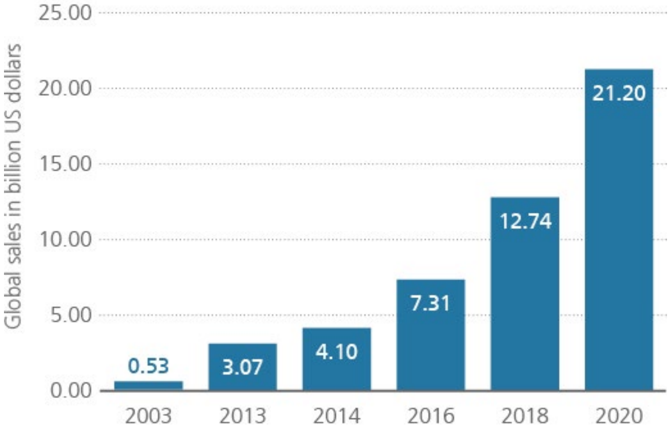
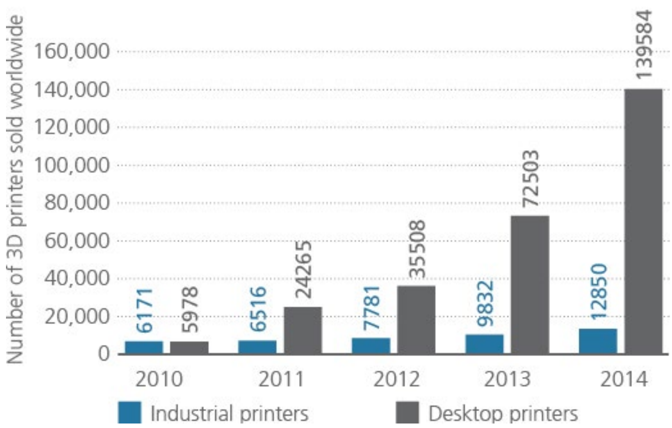


Fig. 2

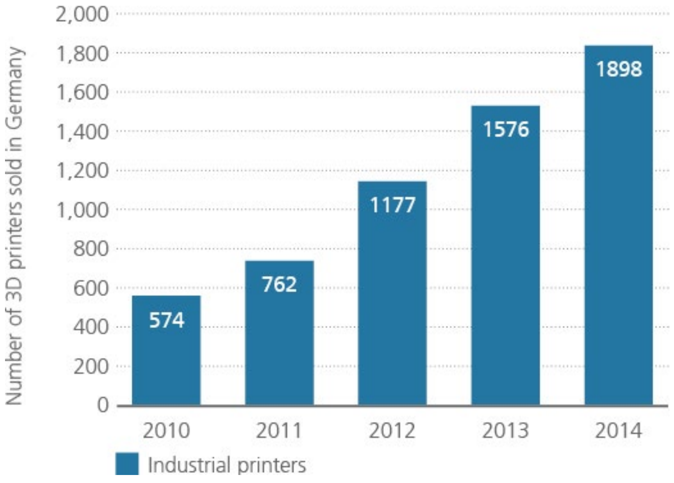
Global sales of industrial and desktop 3D printers (own diagram, data from Wohlers 2015).



A similar trend exists in Germany where sales of industrial 3D printers more than tripled between 2010 and 2014 (Fig. 3). Figures for desktop 3D printers are currently not available. However, a development comparable to the global trend can be assumed in view of the rapidly increasing use of low-cost 3D printers by architects, designers and service providers.

Fig. 3

Sales of industrial 3D printers in Germany (own diagram, data from Wohlers 2015).



3 State of technical development and additive manufacturing applications

Additive manufacturing processes use a host of methods that differ significantly in terms of their technical processes and the materials that can be used. It is, however, possible to identify eight steps in the process chain which most processes have in common (Gibson et al. 2015):

i. A CAD (Computer-Aided Design) system is used to design a virtual, three-dimensional model of an object. The three-dimensional model can also be generated using a 3D scan.
ii. The CAD data is converted to an STL (Surface Tessellation Language) format which serves to describe geometric information of three-dimensional data models. This is the most commonly used interface for commercially available 3D printers.
iii. The STD data is transferred to a 3D printer.
iv. The 3D printer is set up and the print parameters are determined. These include, for instance, the print position in the 3D printer, the atmosphere and temperature in the printing chamber, the properties of the energy source, the material characteristics as well as the layer thickness and the printing time.
v. The object is usually printed by an automated process in the 3D printer.
vi. The printed object can usually be directly removed from the 3D printer.
vii. Depending on the particular printing process, the printed object must undergo several postprocessing steps, such as removal of excess printing material (powder) or infiltration of binder into the object in order to achieve an acceptable strength.
viii. The additively manufactured objects can now be used or undergo aftertreatment, such as priming or painting, depending on their final use.

Powder-based and extrusion processes are the most common methods in additive manufacturing (VDI 2014). Powder-based processes use a thin powder (metal, ceramic, etc.) layer that is applied to a surface and laser-melted to form a defined contour which solidifies after setting. A new powder layer is subsequently applied and the process repeated (PBF process). Extrusion processes use thermoplastic material that is made malleable by a heated nozzle and deposited to form defined geometries (EB process). Table 2 provides a comprehensive overview of commonly used processes, whilst Table 3 contains a list of usable materials and application areas.

Table 2

Additive manufacturing processes and usable materials (adapted according to Gibson et al. 2015).

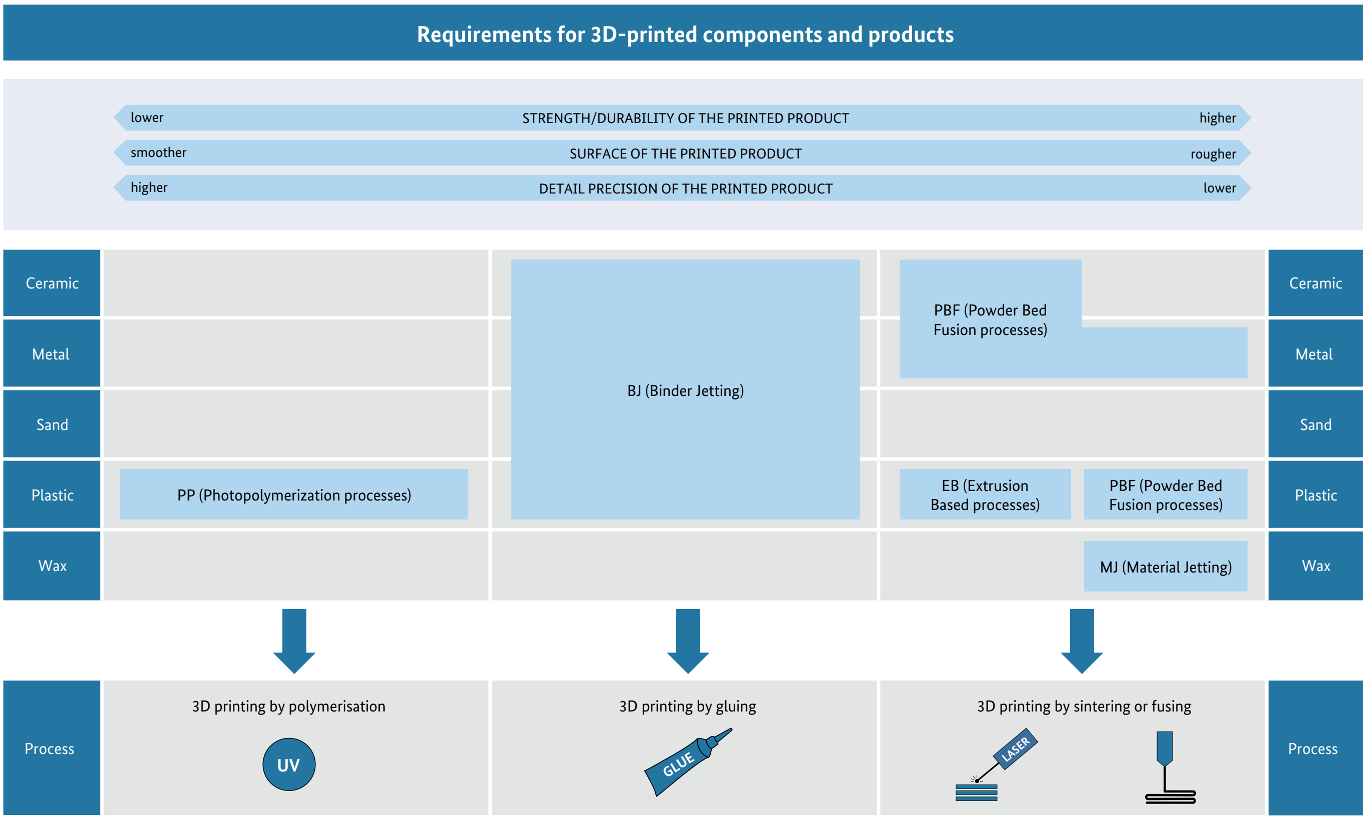
Process	Description
Powder Bed Fusion processes (PBF)	In the PBF process, one or more thermal sources – typically lasers or electron beam sources – are used to sinter or fuse thin powder layers that are placed in a defined printing chamber. Excess powder residues must be removed from the parts after printing.
Extrusion Based processes (EB)	EB processes can be divided into physical and chemical processes. In chemical EB processes, a liquid is applied through a nozzle and solidifies in a chemical reaction. In physical EB processes, thermoplastic material is melted, extruded and placed onto a heated build platform by a heated nozzle. This process is often also called fused deposition modelling (FDM).
Photopolymerization processes (PP)	PP processes use liquid photopolymers that are bonded to a substrate in dot or layer-type patterns so that the polymer solidifies. During the process, the build platform is immersed in the photopolymer. The most common UV source is a laser.
Material Jetting (MJ)	MJ processes usually apply drops of liquid photopolymers or waxes via a printing head to a build platform where they are then polymerized by UV light. The continuous stream (CS) and DOD methods have become the most frequently used processes for drop depositing.
Binder Jetting (BJ)	In BJ processes, a binder is applied to powder layers and infiltrates these one after another, thereby forming a three-dimensional object. This process is also called 3D printing (3DP). After printing, the objects may be additionally infiltrated with further binders or undergo thermal treatment in order to increase their strength, for example.
Sheet Lamination processes (SL)	In SL processes, thin, bidimensional sheets are cut out from a material and joined together layer by layer so that a three-dimensional object is produced.
Directed Energy Deposition processes (DED)	In DED processes, a laser or an electron beam source simultaneously melt the substrate and the material to be deposited on the substrate and continuously feed these to the printing head. In contrast to PBF processes, the material is fused during deposition.

Table 3
Usable materials and applications (adapted according to Gibson et al. 2015; additively.com 2016).

Process	Materials	Areas of application
Powder Bed Fusion processes (PBF)	Thermoplastic materials and elastomers, especially poly-amide or nylon; metals, such as stainless steel and tool steel, titanium and alloys; aluminium alloys; ceramic	Prototypes for form and fit tests as well function tests; ancillary parts (templates, gauges, etc.), tools for injection moulding can be made of hot-working steel; small-series parts and unique pieces
Extrusion Based processes (EB)	Thermoplastic materials, espe-cially polylactides; acrylonitrile-butadiene-styrene	Prototypes for form and fit tests as well function tests; ancillary parts (templates, gauges, etc.), small-series parts
Photopolymerization processes (PP)	Photopolymere	High-precision prototypes and prototypes with good surfaces for visual tests as well as form and fit tests; master patterns, injection moulding tools for very small series
Material Jetting (MJ)	Photopolymers; wax	Prototypes with high surface precision; high-precision casting models and casting models with good surfaces, especially for medical devices, dental and jewellery applications
Binder Jetting (BJ)	Starch and water-based binders; metals and bronze or plastic materials; sand and plastic materials; ceramic and plastic materials	Prototypes in full colour for form and fit tests; green parts; master patterns for casting; moulds and cores made of special casting sand
Sheet Lamination processes (SL)	Paper; metals; plastic materials; ceramic	Prototypes in different colours for form and fit tests
Directed Energy Deposition processes (DED)	Metals; plastic materials; ceramic	see PBF

Fig. 4

Requirements for components and products made by additive manufacturing, as well as possible processes and materials. (Note: The MJ process can also be applied in conjunction with photopolymers. The objects printed have a high degree of detail and smooth surfaces.) (Adapted according to additively.com 2016) © iit



Depending on the materials to be used and the requirements for components and products, different methods of additive manufacturing are available to users (Fig. 4).

At both national and international level, the complete value chain is involved in the development processes. These include technology suppliers (scanners and CAD; material; hardware; etc.), research institutes (processes; materials; design; standards; etc.), users (production; processing; etc.) as well as service providers (processes; automation, business models) (VDMA 2015). Consumers as another important stakeholder group could become increasingly important in future. However, additive manufacturing is currently rarely found in Germany households; a heterogeneous group of early technology users and user-innovators – often referred to as "maker movement" – represent the only user community.

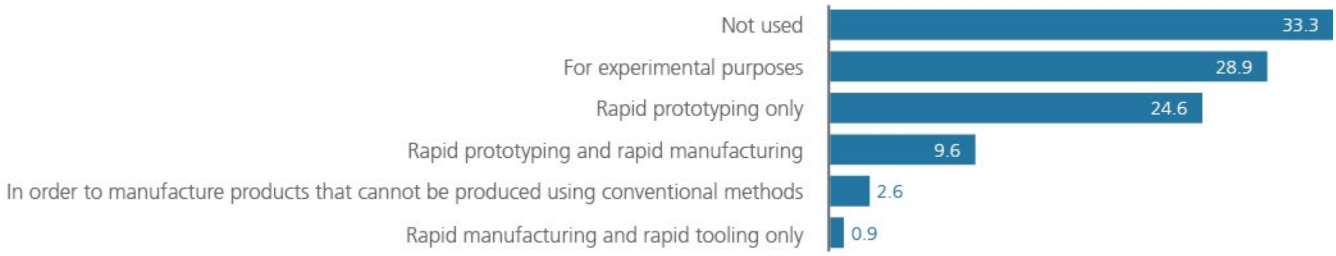
The different additive manufacturing processes can be allocated to three major sector-spanning application fields:

1. Rapid prototyping uses AM processes for the quick manufacture of sometimes even functional prototypes and sample components.

2. Rapid tooling uses AM processes for tool and mould making with a focus on the timely manufacture of complex tools, for instance, for plastic injection moulding.
3. Rapid manufacturing uses AM processes for the quick, flexible manufacture of parts and series.

A user poll from 2014 (Fig. 5) shows that additive manufacturing is used primarily for rapid prototyping and experimenting (PwC 2015). However, recent trends suggest that additive manufacturing is increasingly also being used for rapid manufacturing and rapid tooling with users expecting considerable development potential for the technology. Furthermore, the possibilities of additive manufacturing and especially of new production methods are being discussed extensively among the general public.

Fig. 5
Use profiles of additive manufacturing at companies (adjusted according to PwC 2015)



Parts and products manufactured by rapid tooling and rapid manufacturing must fulfil the same high quality standards as conventionally manufactured parts, and they may also require certification just like their conventional counterparts. Automated, non-destructive testing has an important role to play here as a downstream step in the additive manufacturing process chain. These methods include, for instance, ultrasonic and other testing methods to assess the quality of parts on the basis of 3D scans.

It is neither possible nor helpful to assign individual AM processes to single fields of application because most additive manufacturing processes can be used beyond the boundaries of individual application fields. For an overview of the technological maturity of the three commonly used processes (PBF, EB and PP), Fig. 6 shows the fields of application in relation to the different sectors of industry. Note that the PBF process usually requires a complex technical infrastructure and is therefore predominantly used in industrial applications whilst the EB and PP processes are also used in non-industrial applications.

Fig. 6

Sector-specific fields of application of the most commonly used methods*.
* Own assessment, validated by the „Additive Manufacturing" committee of VDI. © iit

Industry	Powder Bed Fusion processes (PBF)			Extrusion Based processes (EB)			Photopolymerization processes (PP)		
	Prototyping	Tooling	Manufacturing	Prototyping	Tooling	Manufacturing	Prototyping	Tooling	Manufacturing
Automotive industry	✓	✓	✓	✓	✓	✓	✓	×	•
Architecture, furniture industry, design and arts	✓	×	✓	✓	×	✓	✓	×	✓
Electrical engineering and electronics industry	✓	✓	✓	✓	✓	✓	✓	×	×
Film and entertainment industry	✓	×	×	✓	×	✓	✓	×	✓
Aerospace industry	✓	✓	✓	✓	✓	✓	✓	×	×
Medical devices, prosthetics, dental devices, other medical products	✓	✓	✓	✓	✓	✓	✓	✓	×
Food industry	×	×	×	✓	×	•	×	×	×
Defence industry	✓	✓	✓	✓	✓	✓	✓	×	×
Sports equipment industry	✓	✓	✓	✓	×	×	✓	×	×
Toys industry	×	✓	✓	✓	×	✓	✓	×	✓
Textiles and garment industry	✓	×	✓	✓	×	✓	✓	×	×
Science	✓	•	✓	✓	×	×	✓	×	×

✓ Technology is mature/already in productive use × Technology is not yet mature/not relevant • Technology is still in the development stage

Explanations:

Rapid **prototyping** uses AM processes for the quick manufacture of sometimes even functional prototypes and sample components.

Rapid **tooling** uses AM processes for tool and mould making with a focus on the timely manufacture of complex tools, for instance, for plastic injection moulding.

Rapid **manufacturing** uses AM processes for the quick, flexible manufacture of parts and series.

4 Research, development and the situation with support measures

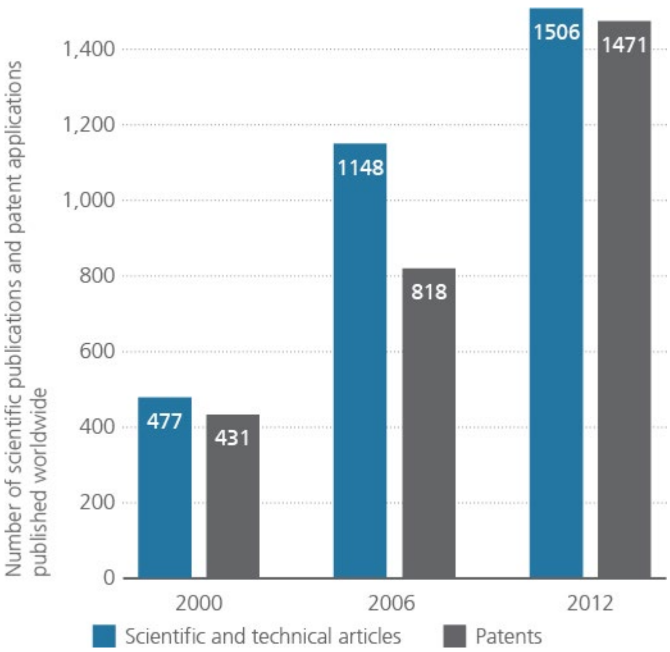
Whilst publications in technical and scientific magazines are a good way of presenting scientific work at universities and research institutes, patents are a good indicator for measuring research and development work by companies and scientific facilities.

The number of technical and scientific articles focusing on additive manufacturing published each year tripled between 2003 and 2012 (Fig. 7). Between 2000 and 2014, scientists in Germany ranked third after the US and China in terms of the number of publications. On an international scale, publications by scientists in Germany achieved a high Hirsch index[3]. In a global comparison, three German universities were among the 30 most important research institutes in the field of additive manufacturing (EFI 2015).

3 The Hirsch index (h-index) is an indicator for the quality of scientific publications. It reflects the citation impact of a scientist's publications.

Fig. 7

Number of scientific publications and patent applications published between 2000 and 2012 (adapted according to EFI 2015).



The number of PCT patent family applications in the field of additive manufacturing also more than tripled between 2003 and 2012 (Fig. 7), with the US and Japan taking the clear lead in 2012. Germany was fourth after China.

Support and funding measures for additive manufacturing[4] in Germany primarily focus on specific application areas. Additive manufacturing processes are supported as part of institutional promotional programmes[5] as well as project funding programmes by the German government. Two current support measures by the Federal Ministry of Education and Research are the programmes "Additive-generative manufacturing – the 3D revolution for products manufactured in the digital age" (term: 2013 to 2020; total budget: €45m) which is supported under the "Twenty20" regional promotional programme as well as "Additive manufacturing – individualised products, complex mass products, innovative materials (ProMat_3D)" which are part of the German government's new high-tech strategy. The support measures particularly aim to:

- develop additive-generative manufacturing to a key technology
- establish sustainable network structures
- boost export demand
- position Germany as a leading supplier
- foster production and material research.

An evaluation[6] of the UFORDAT, GePris and "Förderkatalog" (promotional catalogue) databases (Fig. 8) shows that material development is the focus of the by far largest part of projects in the field of additive manufacturing

4 This refers to support and promotional measures for all technologies related to additive manufacturing, i.e. beyond pure process engineering.

5 This specifically applies to basic funding of research institutes, such as FhG, MPI, etc.

6 The search terms "3d druck", "3d-druck", "additive manufacturing" and "additive fertigung" were used to search for promotional projects in the following databases: Environment research database of the German Environment Agency (UBA) – UFORDAT (http://www.umweltbundesamt.de/ themen/nachhaltigkeit-strategien-internationales/information-als-instrument/ umweltforschungsdatenbank-ufordat); DFG - GePris (http://gepris.dfg.de/); Promotional portal of the German government (http://foerderportal.bund.de)

that are supported and promoted in Germany. In contrast to this, the support agenda for research and development projects contains a smaller number of ICT projects focusing on smart production services, modelling tools as well as sustainability and resource efficiency.

Fig. 8

Thematic classification of 35 additive manufacturing projects previously or currently supported in Germany in the field of additive manufacturing that were analysed as part of the database research (databases: UFORDAT, GePris and „Förderkatalog" (promotional catalogue). Promotional projects can cover one or more focal topics.

In a European context, support measures are currently based on overarching programmes and application areas. A specific support programme for AM is currently not known (EFI 2015).

An evaluation of the CORDIS database[7] (Fig. 9) shows that the two framework programmes FP7 and Horizon 2020 in Europe focus their support measures on interdisciplinary projects covering more than just one topic. Of the 63 additive manufacturing projects supported in Europe, an above-average share of promotional measures is directed towards projects with a focus on material development. Furthermore, projects focusing on smart production services, sustainability and resource efficiency as well as modelling tools account for a higher share than projects receiving national support. The funding available for the 63 projects total around €160m.

Fig. 9

Thematic classification of funded European projects in the field of additive manufacturing that were analysed as part of database research (database: CORDIS).

The "National Network of Manufacturing Innovation" was launched in the US in 2012 in order to promote the National Additive Manufacturing Innovation Institute[8] that was bestowed with 50 million US dollars by the US government (EFI 2015). The Chinese government is planning to provide funds of 245 million US dollars in order to support additive manufacturing in the near future. At present, ten research institutes have been established via the government-supported Asian Manufacturing Association (AMA) (EFI 2015). The support and funding situation in Europe, Asia and the US can be generally considered to be relatively balanced.

7 The search terms "3D-Print*" and "additive manufacturing" were used to search for promotional projects in the following databases: Community Research and Development Information Service of the European Commission – CORDIS (http://cordis.europa.eu/). Projects from the two framework programmes FP7 and Horizon 2020 were included (dated retrieved: 16 February 2016).

8 https://americamakes.us

5 Research demands and prospects

Additive manufacturing has its origins in prototype and small-series manufacturing. In order to achieve maximum flexibility, the degree of process automation was deliberately kept low so that processes still require a high level of manual intervention (VDI 2014). As a result, the core technologies of additive manufacturing processes are already quite mature, but what is now especially needed are ICT-based solutions for the improved use and integration of additive manufacturing processes in order to open up their full potential for future use. As mentioned earlier, research and development projects in Germany focusing on the relevant key areas of modelling tools, smart production services as well as sustainability and resource efficiency still lag far behind projects related to materials. This means that action is needed as outlined below.

5.1 Intuitive modelling tools

The basis for AM objects are virtual, three-dimensional models which are usually generated by CAD programmes or using 3D scanners. Experts usually consider the use of 3D design programs and the creation of 3D models to be unproblematic, and experts, especially engineers, are familiar with customary methods whilst alternative modelling concepts, such as subdivision modelling, are penetrating markets only slowly.

Software applications that are used to design and present three-dimensional models for additive manufacturing still have one downside: These design programs are unable to present and/or transpose important information, such as the assignment of material properties or rigid-body simulations using the finite elements method (FEM). Additional software solutions are then necessary which interpret the 3D data in a completely different way. This leads to compatibility problems and a loss of time when the virtual AM objects may have to be adjusted, thereby impeding attempts to automate additive manufacturing process chains. Furthermore, the use of different software programs is user-unfriendly and error-prone. Integrated software solutions are therefore a precondition for additive manufacturing as part of automated series production.

The user experience of design programs for consumers is given relatively poor marks. Private users and lay people in industry planning to use additive methods still depend on design data which must be either purchased or which is publicly available. Users wishing to design or modify products on their own will need design programs with intuitive user interfaces. Research to enable the intuitive use of modelling tools is already underway and some concepts, such as generative modelling, are already commercially available. However, more intuitive human-computer interfaces will probably be needed in order to enable private users to design or adapt 3D models for 3D printing. Although the majority of private users have IT skills, handling 3D data poses a major challenge, especially when it comes to technical design issues. In order to put the potential of AM to optimum use, user interfaces must be developed which are specifically geared to the third dimension and which integrate further technologies, such as mobile augmented reality (Astor et al. 2013). This would also benefit industrial users.

Recommended action

- Development of modelling tools and user interfaces for private users with the highest possible degree of intuitive user interaction
- Development of modelling tools and file formats which enable and/or support the modelling of shapes and behaviours as well as the simulation of component properties
- Development of modelling tools for the machine-interpretable description of objects (morphology, material properties and porosities, component behaviour, component simulation, etc.)

5.2 Smart production services and process integration

One particular downside at present is the still insufficient degree of automation in additive manufacturing processes. The technology is still a long way from integration into other production chains. Furthermore, a current trend suggests that machine manufacturers strongly curtail possibilities for individual user to enter process parameters and that parameter set-ups must be obtained from the manufacturer for different materials or applications. This approach can open up new business fields for manufacturers to provide services. However, the innovation potential can be seriously affected by such a restriction. Another important factor for successful process integration is the application and further development of customary quality assurance processes, such as non-destructive testing (VDI 2016a).

Besides current challenges, i.e. automation of AM processes and smooth combination with other processes – the role of Industry 4.0 could become increasingly important in future. The freedom of design of automation processes in AM offers a host of options for the best possible adaptation of this technology to the smart factories of the future where machines, equipment and logistics systems will exchange information as globally interconnected cyber-physical systems. Ideally, AM could be vertically integrated with commercial systems and horizontally with distributed process chains with realtime control capability.

Communication within the cyber-physical systems is one of the greatest challenges when it comes to leaving the era of mechatronics for Industry 4.0. Besides the rapidly increasing complexity of future digitised and interconnected production systems where AM will have a key role to play, information security, availability and stability of communication paths and data as well as coexistence and interoperability will be further challenges. This includes the development of new realtime production control tools as a basis for quasi-automatic adjustment and optimisation of production in light of adaptive boundary conditions.

Recommended action

- Complete automation of additive manufacturing process chains in order to make the processes fit for use as part of automated series production (for instance, adjustment of planning and execution systems, continuous data supply, feeding of printers with print material, removal of printed objects)
- Further development and adaptation of quality assurance tools (for instance, non-destructive testing methods based on ultrasonic and 3D monitoring)
- Automated adjustment of virtually planned and real production processes, so that systems can, for instance, be adapted automatically when deviations occur
- Development of communication standards and tools for integrating additive manufacturing into further production processes and smart factories

5.3 Sustainability and resource efficiency

Production-on-demand[9] and production-on-site[10] concepts in conjunction with additive manufacturing will help to save logistics costs, avoid overproduction and reduce transport distances and time.

A general statement as to whether additive methods are generally more ecological than generative processes is not yet possible. This must be examined from case to case, depending on the particular process and application. However, additive methods are expected to enable significant savings, for instance, because they can be used to implement complex structures and therefore new lightweight construction concepts. Furthermore, it is also expected that additive manufacturing processes will require less material than subtractive manufacturing (turning, milling, drilling, etc.). However, two important

9 Additive manufacturing enables on-demand production of parts.
10 Additive manufacturing enables on-site production of parts.

factors are overlooked here. Many additive processes use support structures which are often not recycled. Moreover, the printing materials can degrade during the printing process (heat, light), so that material losses can be as high as 30% (PBF processes) or even 45% (PP processes) (Bechthold et al. 2015). However, recent studies suggest that the relevant factor for the ecobalance is the use profile of the machines, with a high degree of utilisation of 3D printers improving their ecobalance[11] significantly. Machine sharing concepts are therefore an important strategy for the sustainable and resource-friendly design of additive manufacturing. This requires smart networking of AM machines at different sites as well as an adaptive logistics concept – a challenge for the future.

Social factors are another important category which must also be considered in the analysis of environmental impacts. The introduction of additive manufacturing as a desktop process can lead to increased resource consumption as a result of changed consumption patterns in society (think, for instance, of desktop paper printers). These so-called rebound effects are still largely unexplored in the area of additive manufacturing.

Recommended action

- Development of concepts and technologies for building 3D printer networks in order to achieve optimum utilisation beyond site boundaries
- Development and adaptation of logistics concepts and technologies that support 3D printer sharing concepts in realtime
- Examination of possible rebound effects and ecobalances of the technologies and processes used as well as their applications

11 An ecobalance compiles all environmental impacts which a product generates during its lifecycle.

5.4 Innovative materials

Besides ICT-specific aspects, new materials are an important driver for additive manufacturing to become an established process in the future. These include, first and foremost, powders for PBF processes, filaments and pellets for EB processes as well as photopolymers and waxes for printing processes (such as PP or MJ processes) which are based on liquid materials. Composite materials (such as fibre-reinforced powders or filaments), biomaterials and biological materials (tissues, cells, proteins, etc.) are a special case. These materials are still very rare on the market or have not yet reached market maturity.

Furthermore, limit values for powder characteristics are still lacking when it comes to determining when a powder is suitable or unsuitable for PBF processes, for example. At present, even unsuitable powders are made suitable by skilfully adjusting the process parameters. What's more, the ageing behaviour of photopolymers, for instance, due to storage or the printing process (temperature or light) is still largely unknown (VDI 2016a). This lack of knowledge is a key factor which determines the amount of process waste in additive manufacturing. Due to concerns regarding quality impairment, materials are often subjectively classified as being unsuitable for the printing process and therefore either disposed of or "downcycled" for other processes, such as injection moulding.

Whilst the diversity of materials and the knowledge of these substances can be considered to drive innovation, a major obstacle exists in the form of the price development of commercially available AM materials which counteracts the further propagation of industrial-scale additive manufacturing. Prices of 175 to 250 US dollars per kilogramme of industry-grade AM thermoplastic materials and photopolymers correspond to multiples of those for conventional plastic materials for injection moulding which are available at 2 to 3 US dollars upwards per kilogramme (Wohlers 2015). Filaments for EB processes in desktop printing are already available from 30 US dollars per kilogramme. Reasons for the high price include, amongst other things, low competition as well as limited sales.

Recommended action

- Develop new materials
- Optimise tried-and-tested materials
- One focus should be on composite materials, biomaterials and biological materials.
- Examination of ageing behaviour and determination of specific powder characteristics for additive manufacturing.
- Development of concepts for material recycling and energy savings through OCT-based analysis and evaluation systems

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7 Appendix

7.1 Standards

Technical Committee 261, "Additive Manufacturing", of the International Organization for Standardization (ISO) is in charge of international standardization in the field of additive manufacturing.

The committee was set up in February 2011 in response to a request by the Working Group NA 145-04-01 AA "Fundamentals and Test Methods" in the "Additive Manufacturing" Division which was established shortly before as a national body in the German DIN organization. The German body decided to drive the issue of additive manufacturing at an internal level.

Members of the German standardization body include manufacturers of machines for additive manufacturing, representatives from research and academia as well as users, for instance, from the automotive and aviation sectors in order to develop fundamentals for additive manufacturing. The Working Group NA 145-04-01 AA "Fundamentals and Test Methods" is in charge of standardisation work in order to determine fundamentals and test methods for additive manufacturing processes. The working group is the German counterpart of the newly established ISO/TC 261 "Additive Manufacturing" and the pertinent four working groups.

The German body's application for the ISO/TC 261 secretariat was successful, so that both the secretariat of the TC 261 "Additive Manufacturing" and of the WG 2 "Methods, processes and materials" in the TC 261 are now led by Germany.

DIN's assumption of the ISO/TC secretariat for additive manufacturing methods was intended to underline Germany's intention and possibilities to take on an internationally leading role in this area too.

Based on VDI standards 3404/3405, the first ISO standard series on "Additive manufacturing" was developed in recent years in the form of ISO 17296 "Additive Manufacturing". It consists of four parts each of which was developed by a separate working group:

- **ISO/TC 261/WG 1** *Terminology* (secretariat: SIS, Sweden): ISO 17296-1, Additive manufacturing – General principles – Part 1: Terminology
- **ISO/TC 261/WG 2** *Methods, processes and materials* (secretariat: DIN, Germany): ISO 17296-2: Additive manufacturing – General principles – Part 2: Overview of process categories and feedstock
- **ISO/TC 261/WG 3** *Test methods* (secretariat: AFNOR, France): ISO 17296-3: Additive manufacturing – General principles – Part 3: Main characteristics and corresponding test methods
- **ISO/TC 261/WG 4** *Data processing* (secretariat: BSI, UK): ISO 17296-4: Additive manufacturing – General principles – Part 4: Overview of data processing
ISO 17296 parts 3 and 4 were published in autumn 2014 and part 2 in January 2015 while the publication of part 1 is planned for summer 2015.

After ISO and ASTN Committee F 42 "Additive manufacturing technology" (USA) agreed to co-operate, the following ASTM standards were adopted:

- ASTM F 2921, Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies (ISO/ASTM 52921:2013-06) and
- ASTM F 2915, Standard Specification for Additive Manufacturing File Format (AMF) (ISO/ASTM 52915:2013-06)

als ISO/ASTM standards via the fast-track procedure. Work on adopting ASTM F 2915 "Specification for Additive Manufacturing File Format (AMF) Version 1.2" has also begun.

This is the first time ever that the ISO and ASTM standardisation organisations have co-operated so closely. After a joint strategy for co-operation between ASTM F 42 and ISO/TC 261 was developed in 2013, joint groups were set up which have begun developing the highest-priority standardisation projects in which ISO and ASTM experts are equally represented. The joint groups are working on the following topics: "Terminology", "Standard test artifacts", "Requirements for purchased AM parts", "Design guidelines", "Standard Specification for Extrusion Based Additive Manufacturing of Plastic Materials", "Standard Practice for Metal Powder Bed Fusion to Meet Rigid Quality Requirements", "Specific design guidelines on powder bed fusion" and "Qualification, quality assurance and post processing of powder bed fusion metallic parts NDT for AM parts".

German content is to a large extent generated by VDI's "Additive Manufacturing" Technical Committee. The Technical Committee is also in charge of supervisory and support activities for VDI standards 3404/3405 for additive manufacturing, the contents of which are to a large extent also found in ISO/ASTM 52792 on terminology as well as the above-mentioned ISO 17296-2 to 4 series.

The VDI committees perform round robin tests[1] on a regular basis, for instance, in order to determine material characteristics as a basis for identifying the state of the art which is then transposed to international standards via VDI standards and the national DIN working groups. This is also reflected by the membership of the DIN and ISO bodies while the German representatives are mainly experts from the VDI technical committee.

One may conclude that the German perspective of "additive manufacturing" and German interests are comprehensively represented in the international bodies and committees and that the experts from industry and academia represented there are making a very active contribution.

1 Round robin Test: a quality assurance method for measuring methods as well as measuring and test labs.

Identical samples are tested and examined in different labs using identical and/or different methods. The comparison of the results permits statements concerning measuring accuracy and the determination of material characteristics. Round robin tests are also used to test rules for measuring methods

Further reading:

- Jahresberichte des Normenausschusses Werkstofftechnologie (NWT) im DIN[2]
- VDI Statusreport „Additive Fertigungsverfahren", September 2014[3], Aktualisierung in der ersten Jahreshälfte 2016 erwartet (www.vdi.de/HandlungsfelderAM)

7.2 Overview: National research and development projects

The following pages provide an overview of both finished and ongoing promotional projects at national and European level which were considered in the analysis in chapter 4[4]. This list does not claim to be exhaustive and shows only those projects which are related to the four most important fields of action that were discussed in chapter 5: modelling tools, smart production services and process integration, sustainability and resource efficiency as well as materials.

2 http://www.nwt.din.de/cmd?level=tpl-artikel&menuid=46711&cmsareaid=46711&cmsrubid=46739&menurubricid=46739&cmstextid=74924&bcrumblevel=1&languageid=de

3 https://www.vdi.de/technik/fachthemen/produktion-undlogistik/fachbereiche/produktionstechnik-und-fertigungsverfahren/fa105-fachausschuss-additive-manufacturing/statusreport-additive-fertigungsverfahren/

4 The search terms "3D-Print*", "3d druck", "3d-druck", "additive manufacturing" and "additive fertigung" were used to search for promotional projects in the following databases: environmental research database of the German Environment Agency (UBA) - UFORDAT (http://www.umweltbundesamt.de/themen/nachhaltigkeit-strategien-internationales/information-als-instrument/umweltforschungsdatenbank-ufordat); DFG - GePris (http://gepris.dfg.de/); "Förderkatalog" (promotional catalogue) of the German government (http://foerderportal.bund.de/); Community Research and Development Information Service of the European Commission – CORDIS (http://cordis.europa. eu/). Projects from the two framework programmes FP7 and Horizon 2020 were included (dated retrieved: 16 February 2016).

Project	Modelling tools	Smart production services	Sustain-ability	Materials
3D-PolySPRINT: Light-based processing of heterogeneous polymer composites for the quick, additive manufacture of function elements for aural-acoustic transducers http://www.photonikforschung.de/fileadmin/Verbundsteckbriefe/20._Photonische%20Prozessketten/3D-PolySPRINT_Projektsteckbrief_Pro-zessketten_bf.pdf		x		
3D powder printing of calcium phosphate ceramics with spatially resolved adjustment of structure and composition http://gepris.dfg.de/gepris/projekt/55396052				x
3DAMEEA – Additive 3D manufacture of electrical applications http://www.iwb.tum.de/Additive+3D_Fertigung+von+elektrischen+und+elektronischen+Anwendungen-p-1019488.html		x		x
addef: Additively manufactured high-performance components made of titanium alloys and titanium aluminide – process control, characterization, simulation				x
Additive manufacturing of Three-dimensional Surfaces http://gepris.dfg.de/gepris/projekt/278735550				x
Additive manufacturing of single-crystalline superalloys (B02) http://gepris.dfg.de/gepris/projekt/211501246				x
Additive manufacturing of free formed reinforced concrete elements by selective binding with calcium silicate cements http://gepris.dfg.de/gepris/projekt/257344691				x
Additive manufacturing based on ultrasound Polymer melting: process research and technology development				x
Analysis and evaluation of the effects of social and environ-mental issues on environmental policy us-ing the trend analy-sis method				
AutoAdd Integration of generative production method in automobile series production http://www.wbk.kit.edu/wbkintern/Forschung/Projekte/AutoAdd/index.html		x		x

Project	Modelling tools	Smart production services	Sustain-ability	Materials
BioFabNet: Campaign for the use of bio-based plastic materials in 3D printing as a case example of bioeconomics of tomorrow https://www.biofabnet.de/				X
CALM (CFK ALM connection element) – additive manufacturing and joining technologies				X
Additive 3D-manufacturing of light-guiding structures on molded interconnect devices http://gepris.dfg.de/gepris/projekt/257258383				X
Embedding stereolithography – process development for integrating function elements in mechatronic assemblies http://gepris.dfg.de/gepris/projekt/190972254				X
Development and manufacturing of optimized working coil windings for electromagnetic forming using additive manufacturing techniques http://gepris.dfg.de/gepris/projekt/259797904				X
Development of processes for the generation of high-precision STL files for the 3D printing of a stellated dodecahedron	X			
Research and Development of a Nanostructure Deposition System http://gepris.dfg.de/gepris/projekt/247352488				X
Generatively manufactured ceramic parts with three-dimensionally function-graded structures http://gepris.dfg.de/gepris/projekt/114052652				X
GenErgie, increasing energy efficiency through generative manufacturing using selective laser melting https://www.tib.eu/de/suchen/download/?tx_tibsearch_search%5bdocid%5d=TIBKAT%3A824625781&cHash=5d9da70bf06cad90ca616bfc8e1c5f7c#download-mark			X	
Device for additive manufacturing in the powder bed by means of electron beam http://gepris.dfg.de/gepris/projekt/246541036				X
Green Factory Bavaria, resource-efficient powder and beam-based additive series manufacturing http://www.greenfactorybavaria.net/		X	X	X

Project	Modelling tools	Smart production services	Sustain-ability	Materials
Manufacture of three-dimensional function parts made of high-performance ceramic using direct ink jet printing http://gepris.dfg.de/gepris/projekt/52977705				■
Three-dimensional printing process for the production of near-standard components with property gradients http://gepris.dfg.de/gepris/projekt/163148346				■
High-order immersed-boundary methods in solid mechanics for structures generated by additive processes http://gepris.dfg.de/gepris/projekt/255496529	■			
In-situ formation and additive manufacturing of nano particulate reinforced metal matrix composites by laser metal deposition http://gepris.dfg.de/gepris/projekt/229707301				■
Integrative production technology for energy-effi-cient turbo engines TurPro http://www.turpro.de/de/index		■		
Combination machine for laser deposition welding of powder in a 5-axis milling machine http://gepris.dfg.de/gepris/projekt/279885319		■		
MAC4U, Mass customization for individualized product expansions http://www.mac4u-projekt.de/		■		
PROPRINT: Manufacture of series-identical prototypes by 3D printing http://www.produktionsforschung.de/PFT/verbundprojekte/vp/index.htm?VP_ID=539		■		■
RADIKAL, resource-saving material substitution by additive and smart FeAl material concepts for adapted lightweight and function construction http://www.matressource.de/projekte/radikal/			■	■
Rapid Prototyping of microstructured ceramic and metal parts by Powder Fused Deposition modeling http://gepris.dfg.de/gepris/projekt/283446569				■

Project	Modelling tools	Smart production services	Sustain-ability	Materials
Robocasting of 3D-ceramic macrocellular structures with tubular filaments http://gepris.dfg.de/gepris/projekt/231507867				■
Robot-based 3D laser machining centre http://gepris.dfg.de/gepris/projekt/163724033		■		
PriMa3D, screen-printed components for electric drives http://www.effizienzfabrik.de/de/projekte/elektrische-antriebe-detail/prima3d/737/		■		■
Evaporation phenomena during selective electron beam melting and their influence on material properties http://gepris.dfg.de/gepris/projekt/187191007				■

7.3 Overview: European research and development projects

Explanations: see chapter 7.2, page 27.

Project	Modelling tools	Smart production services	Sustain-ability	Materials
AEROBEAM, Direct Manufacturing of stator vanes through electron beam melting http://ceit.es/en/areas-of-r-a-d/materials/consolidation-of-metallic-and-ceramic-powders/aerobeam-direct-manufacturing-of-stator-vanes-through-electron-beam-melting			■	■
AMAZE, Additive Manufacturing Aiming Towards Zero Waste & Efficient Production of High-Tech Metal Products http://www.amaze-project.eu/		■	■	■
AMCOR, Additive Manufacturing for Wear and Corrosion Applications http://www.amcor-project.eu/		■	■	■
APPROAcH, Antimicrobial and Save 3D-Printable Polymers for Oral Health http://cordis.europa.eu/project/rcn/198670_en.html				■

Project	Modelling tools	Smart production services	Sustain-ability	Materials
BIO-SCAFFOLDS, Natural inorganic polymers and smart functionalized micro-units applied in customized rapid prototyping of bioactive scaffolds http://cordis.europa.eu/project/rcn/108698_en.html	■			■
BOREALIS, the 3A energy class Flexible Machine for the new Additive and Subtractive Manufacturing on next generation of complex 3D metal parts. http://cordis.europa.eu/project/rcn/108698_en.html		■		
CASSAMOBILE, Flexible Mini-Factory for local and customized production in a container http://www.cassamobile.eu/		■	■	
CAxMan, Computer Aided Technologies for Additive Manufacturing https://www.igd.fraunhofer.de/Institut/Abteilungen/IET/Projekte/CAx-MAN-Computer-Aided-Technologies-Additive-Manufacturing	■	■	■	
CerAMfacturing, Development of ceramic and multi-material components by additive manufacturing methods for personalized medical products http://cordis.europa.eu/project/rcn/198348_en.html				■
CopyMe3D: High-Resolution 3D Copying and Printing of Objects http://cordis.europa.eu/project/rcn/191998_en.html	■			
DiDIY: Digital Do It Yourself http://www.didiy.eu/	■			
DIGHIRO, Digital Generation of High Resolution Objects http://www.2020-horizon.com/DIGHIRO-Digital-Generation-of-High-Resolution-Objects%28DIGHIRO%29-s8764.html	■			
DIMAP, Novel nanoparticle enhanced Digital Materials for 3D Printing and their application shown for the robotic and electronic industry http://www.profactor.at/index.php?id=943				■
DLCHHB, Artificial Tissue Actuators by the 3D Printing of Responsive Hydrogels http://cordis.europa.eu/project/rcn/195483_en.html				■
EBMPerform, High-quality, high-speed EBM 3D printing by the integration of high-performance electron sources cordis.europa.eu/project/rcn/196409_en.html				■

Project	Modelling tools	Smart production services	Sustain-ability	Materials
Efficient Cooking, Substainable and efficient food processing and cooking system http://cordis.europa.eu/project/rcn/196527_en.html			■	
FABulous, Future Internet Web-Entrepreneurship for 3D Printing Virtual Fabrication in Europe cordis.europa.eu/project/rcn/192131_en.html		■	■	
Factory-in-a-day, Reduce system integration time to one day http://www.factory-in-a-day.eu/	■	■	■	
FAST, Functionally graded Additive Manufacturing scaffolds by hybrid manufacturing http://cordis.europa.eu/project/rcn/198809_en.html				■
FASTEBM, High Productivity Electron Beam Melting Additive Manufacturing Development for the Part Production Systems Market cordis.europa.eu/project/rcn/100826_en.html		■		
FLOWMAT, Exploiting Flow and Capillarity in Materials Assembly: Continuum Modelling and Simulation cordis.europa.eu/project/rcn/109735_en.html				■
HI-MICRO, High Precision Micro Production Technologies https://www.hi-micro.eu/	■			
HIRESEBM, High resolution electron beam melting http://cordis.europa.eu/project/rcn/100645_en.html				■
IC2, Intelligent and Customized Tooling http://www.ic2-eu.org/		■	■	
IMPRESS, New Easy to Install and Manufacture PRE-Fabricated Modules Supported by a BIM based Integrated Design ProceSS http://www.project-impress.eu/		■		■
INTERAQCT, International Network for the Training of Early stage Researchers on Advanced Quality control by Computed Tomography https://www.interaqct.eu/	■			
LESA, Laser bonding of linear edged super-abrasive blades http://cordis.europa.eu/project/rcn/197560_en.html			■	

Project	Modelling tools	Smart production services	Sustain-ability	Materials
M&M´S, New Paradigms for MEMS & NEMS Integration http://cordis.europa.eu/project/rcn/100236_en.html		■		■
M&M'S+, 3D Printer for Silicon MEMS & NEMS http://cordis.europa.eu/project/rcn/107465_en.html		■		■
M3M, Mobile 3D Modeling http://cordis.europa.eu/project/rcn/198671_en.html	■			
ManSYS, MANufacturing decision and supply chain management SYStem for additive manufacturing http://www.mansys.info/	■	■	■	
MERLIN, Development of Aero Engine Component Manufacture using Laser Additive Manufacturing cordis.europa.eu/project/rcn/97209_en.html			■	
NANOMASTER, Graphene based thermoplastic masterbatches for conventional and additive manufacturing processes http://cordis.europa.eu/project/rcn/101393_en.html				■
NANOTUN3D, Development of the complete workflow for producing and using a novel nano-modified Ti-based alloy for additive manufacturing in special applications. http://cordis.europa.eu/project/rcn/198813_en.html				■
NEXT-3D, Next generation of 3D multifunctional materials and coatings for biomedical applications http://cordis.europa.eu/project/rcn/194379_de.html				■
OPTICIAN2020, Flexible and on-demand manufacturing of customised spectacles by close-to-optician production clusters http://www.optician2020.eu	■	■	■	
Ownerchip, Digital Rights Management Infrastructure For 3D Printed Artifacts http://cordis.europa.eu/project/rcn/194737_en.html		■		
OXIGEN, Oxide Dispersion Strengthened Materials for the Additive Manufacture of High Temperature Components in Power Generation http://cordis.europa.eu/project/rcn/106325_en.html				■
PHOCAM, Photopolymer based customized additive manufacturing technologies http://www.phocam.eu/doku.php		■		

Project	Modelling tools	Smart production services	Sustain-ability	Materials
PICSIMA, Next generation 3D print technology (PICSIMA), which for the first time enables the direct full colour printing of silicone to make soft tissue prostheses, orthoses and removable partial dentures. http://cordis.europa.eu/project/rcn/197141_en.html			■	■
PILOTMANU, Pilot manufacturing line for production of highly innovative materials http://www.pilotmanu.eu/				■
PRINTCR3DIT, Process Intensification through Adaptable Catalytic Reactors made by 3D Printing http://cordis.europa.eu/project/rcn/198358_en.html			■	
RRD4E2, Rational Reactor Design for Enhanced Efficiency in the European Speciality Chemicals Industry cordis.europa.eu/project/rcn/109277_en.html			■	
Scan4Reco, Multimodal Scanning of Cultural Heritage Assets for their multilayered digitization and preventive conservation via spatiotemporal 4D Reconstruction and 3D Printing cordis.europa.eu/project/rcn/197123_en.html	■			
ShapeForge: By-Example Synthesis for Fabrication http://cordis.europa.eu/project/rcn/104922_en.html	■	■		
SIMCHAIN, Development of physically based simulation chain for microstructure evolution and resulting mechanical properties focused on additive manufacturing processes http://cordis.europa.eu/project/rcn/111099_en.html	■			
SMARTLAM, Smart production of Microsystems based on laminated polymer films http://www.smartlam.eu/	■	■		
SPHERESCAFF, The Manufacturing of Scaffolds from Novel Coated Microspheres via Additive Manufacturing Techniques for Temporomandibular Joint Tissue Engineering cordis.europa.eu/project/rcn/189885_en.html				■
ToMax, Toolless Manufacturing of Complex Structures http://www.tomax-h2020.eu/			■	

Project	Modelling tools	Smart production services	Sustain-ability	Materials
ULTRASUPERTAPE, ULTRAfast growth of ultrahigh performance SUPERconducting TAPEs http://cordis.europa.eu/project/rcn/197529_en.html				
VESCEL, Vascular Engineering on chip using differentiated Stem Cells http://cordis.europa.eu/project/rcn/198695_en.html				
VINDOBONA, VINyl photopolymer Development Of BONe replacement Alternatives cordis.europa.eu/project/rcn/103347_en.html				
Volumental: The Cloud-Delivered 3D Scanning Service Supporting A Future Of Mass Customization https://ec.europa.eu/easme/en/sme/5893/volumental-cloud-delivered-3d-scanning-service-supporting-future-mass-customization				

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