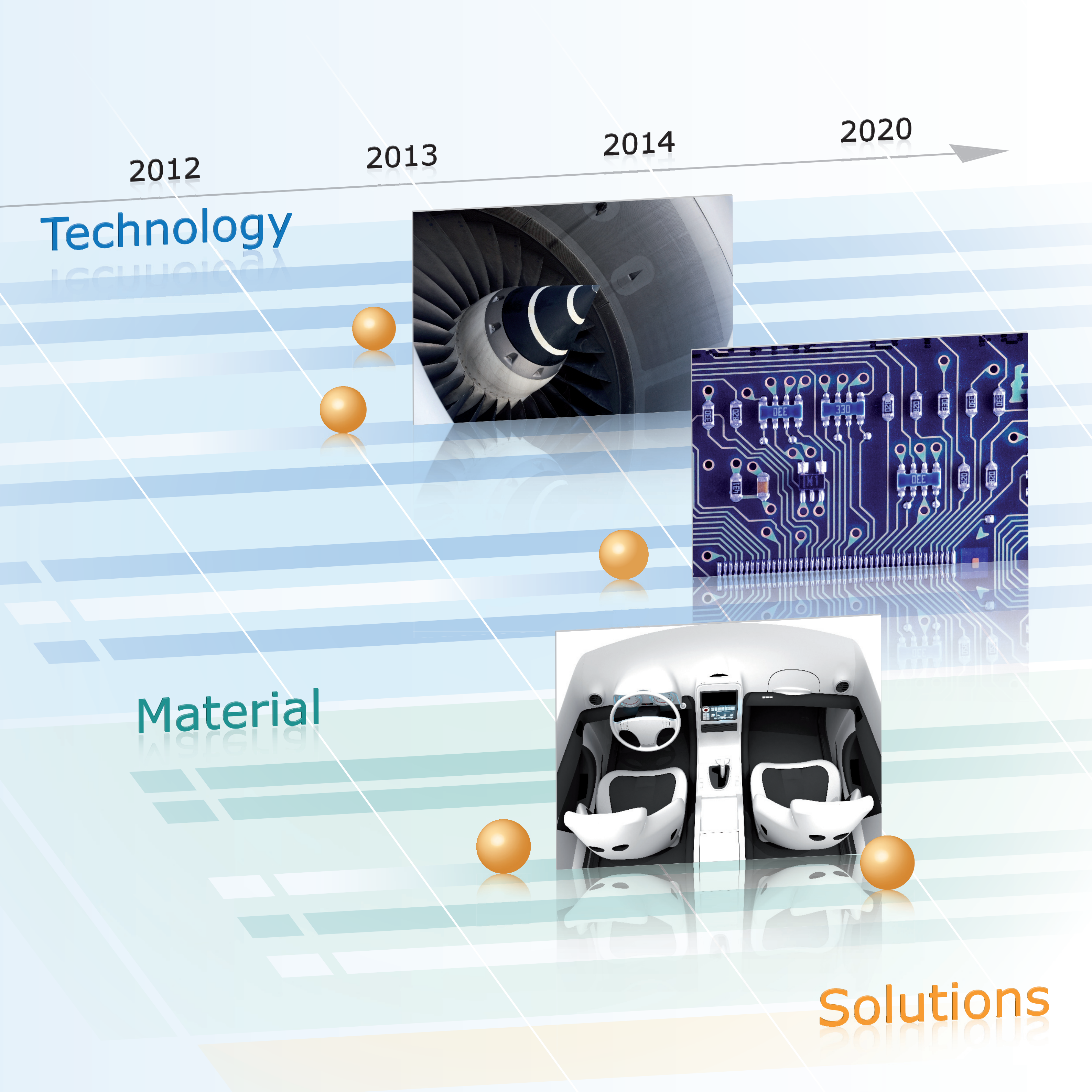
Thinking ahead the Future of Additive Manufacturing –

Innovation Roadmapping of Required Advancements



DMRC
DIRECT MANUFACTURING RESEARCH CENTER

HEINZ NIXDORF INSTITUTE
University of Paderborn
Product Engineering
Prof. Dr.-Ing. Jürgen Gausemeier

Imprint

Author

Prof. Dr.-Ing. Jürgen Gausemeier
(Scientific Coordination)

Niklas Echterhoff
Marina Wall

Heinz Nixdorf Institute
Chair for Product Engineering
Fuerstenallee 11
33102 Paderborn
Germany

Phone +49 5251 | 60-6267
Fax +49 5251 | 60-6268

E-mail: Juergen.Gausemeier@hni.uni-paderborn.de
Internet: http://www.hni.uni-paderborn.de/en/pe

By Order of

University of Paderborn

Direct Manufacturing Research Center (DMRC)
Mersinweg 3
33098 Paderborn
Germany

Phone +49 5251 | 60-5415
Fax: +49 5251 | 60-5409

Internet: http://www.dmrc.de

Assistance

Axel Andraczek
Kristin Bardehle

Preface

In the today's extensive technology-landscape, few technologies have proven to be indispensable. Among these is Additive Manufacturing (AM) – the creation of three-dimensional parts by the consecutive addition of material. Already today, AM is in the clear technological vanguard regarding "Freedom of Design". Which tremendous opportunities will this technology provide in the future? At all, which benefits can be yielded if we advance AM even further?

At Evonik, we actively support Additive Manufacturing since many years with materials – sometimes as build material, sometimes as magic ingredient in tailor made formulations. We saw the perspective of technology changing from a prototyping process to a basically new forming process for materials. Besides all the technical challenges of such a new manufacturing process, the potential advantages for the industry and end users are metaphorically comparable to an iceberg – we are convinced that we do not know most of its potentials yet. We at Evonik are fully committed to develop AM further. Our partnership with the Direct Manufacturing Research Center (DMRC) and supporting its projects is one valuable part of our commitment.

The DMRC is a proactive collaboration of key technology suppliers and forward thinking users who are striving to advance AM-technologies from Rapid Prototyping to dependable Direct Manufacturing (DM) technologies. Given this goal, it is necessary to create a broad awareness of AM's fascinating capabilities among potential users. Reciprocally, technology suppliers need tangible feedback with regard to customer requirements to focus their research. The process of aligning the technological development with future requirements is exactly the process to perform the transition from AM to DM. In the context of this endeavor, the DMRC is carrying out the project "Opportunities and Barriers of Direct Manufacturing Technologies for the Aerospace Industry and adapted others".The goal is a three-part study, lining out opportunities and barriers in the transition of AM into DM.

As of now, the third study is available, focusing innovation roadmapping of promising DM-applications in the aerospace, automotive and electronics industry. Innovation roadmaps indicate when promising applications can be realized via AM as the necessary technological maturity will be reached. The study presents the outcomes resulting from the excellent cooperation of the DMRC with experts from the three industries, AM-technology experts and the project team of the Heinz Nixdorf Institute (Chair of Product Engineering, Prof. Dr.-Ing. J. Gausemeier). Our thanks go to all experts who have supported the DMRC in the creation of this study.

Best regards

Sylvia Monsheimer

Sylvia Monsheimer

Business Unit Performance Polymers
Growth Line Advanced Technology
Evonik Industries AG

Contents

Page

Introduction

The present study is the third of three public studies, resulting from the project “Opportunities and Barriers of Direct Manufacturing Technologies for the Aerospace Industry and adapted others”, performed by the Direct Manufacturing Research Center (DMRC) and the Heinz Nixdorf Institute, University of Paderborn, Germany.

Object of the project are future influences spurring an increase in market relevance of Direct Manufacturing (DM) technologies in the aerospace, automotive and electronics industry, as these were identified as the most auspicious fields for the application of AM. Based on this, a strategic planning of future DM-applications and a planning of technologies required for the most promising applications within the next 10 years, are carried out. This enables the DMRC and its partners to be one step ahead of respectably competitive research centers worldwide. Especially, material and technology suppliers of the DMRC can significantly benefit from the strategic planning of future applications, as it serves as an incentive for their customers to use AM-technologies extensively.

Goal of the project are three public and one confidential study, lining out the opportunities and barriers of DM for the selected industries. The public versions comprise an overview of the results; the confidential version encompasses comprehensive results and is accessible for DMRC partners.

Proceeding in the Project

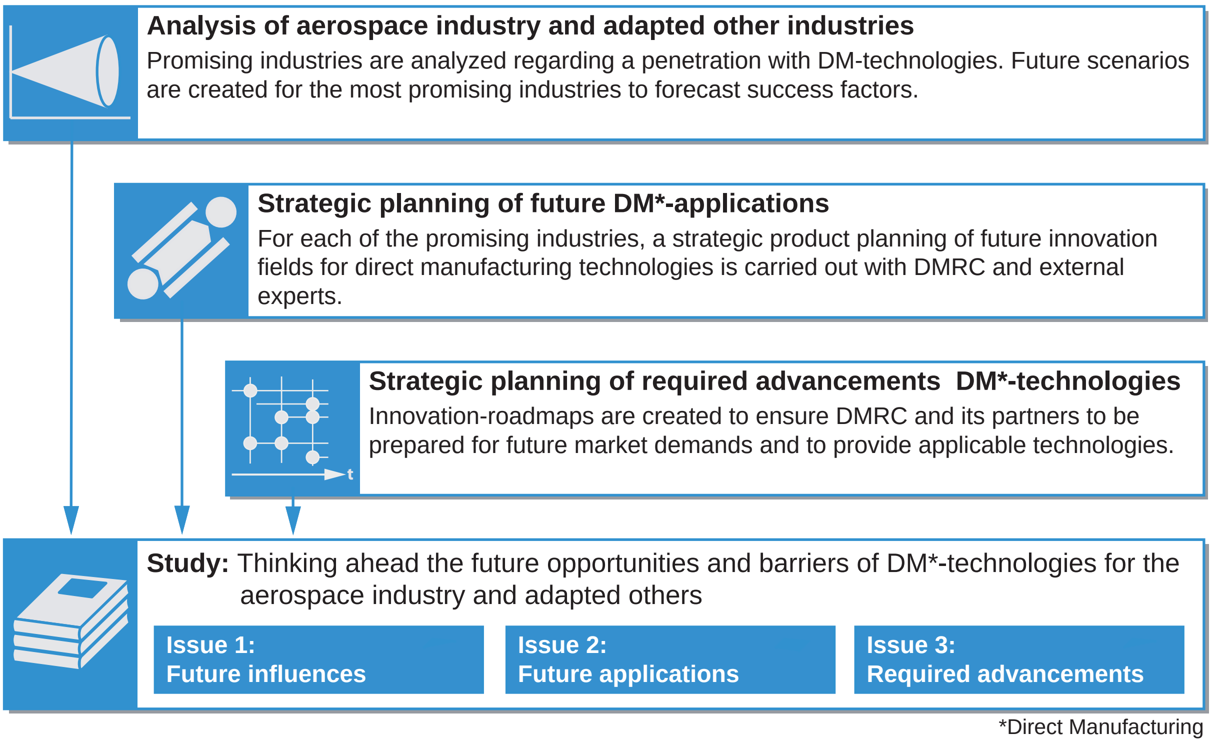


Figure 1: Proceeding in the project

Work package 1 addresses the following questions:

- Which are promising industries for the application of AM-technologies?
- Which are the current success factors to push AM towards DM?
- What are the most auspicious industries?
- Which chances, risks and future success factors for embedding DM-processes into the production do prevail in these industries?

For this purpose, promising industries are assessed regarding the penetration by AM-technologies in the future. For the industries outlined as particularly auspicious for DM, scenarios for the year 2020 are developed. Based on this, future success factors and strategic directions are derived.

Work package 2 covers the following questions:

- Which applications might be replaced by AM-technologies within the next 10 years?
- Which future requirements need to be fulfilled?

To answer these questions, ideas for future applications of DM in the selected industries are developed and clustered to innovation fields. From the identified innovation fields, future requirements are deduced and validated in an expert survey.

Work package 3 answers the following questions:

- Which AM-technologies have the potential to fulfill the requirements of DM in the future?
- Which technological advancements have to be realized to tap the entire potential of AM?
- When can the developed applications be manufactured via AM, as technological advancements will have been realized in accordance to the future requirements?

Therefore, advancements of existing AM-technologies were identified that are required to overcome the challenges revealed in work package 1 and to enable future applications worked out in work package 2. This encompasses advancements of product, material and production technologies.

Within **work package 4**, the confidential and the public studies are compiled. The confidential study provides all information gathered in the project. The public studies cover three issues, each respectively comprising an overview of one work package.

The first study “Thinking ahead the Future of Additive Manufacturing – Analysis of Promising Industries“, comprising an overview of work package 1, was released in May 2011. The second study “Thinking ahead the Future of Additive Manufacturing – Future Applications“, summarizing work package 2, was published in March 2012. Electronic versions of both studies are available on the DMRC web site, under: www.dmrc.de/en.

Proceeding in Study

The present study “Thinking ahead the Future of Additive Manufacturing – Innovation Roadmapping of Required Advancements” presents the results of the project mentioned above. It reveals the advancements of AM-technologies that are required to realize the future application ideas identified in the project. In addition, the study comprises Innovation Roadmaps, indicating when the most required technological advancements will be achieved. The main results emerged from several workshops at the Heinz Nixdorf Institute, Paderborn, Germany and at Boeing, St. Louis, U.S.A. A total of over 40 experts from the DMRC and external firms contributed their knowledge. Moreover, about 150 experts provided their expertise in two expert surveys, conducted by the Heinz Nixdorf Institute and the Direct Manufacturing Research Center.

About 150 experts contributed their expertise for the creation of this study.

Chapter 1: The Business of Additive Manufacturing

The first chapter focuses on the business of Additive Manufacturing, summarizing the results of work package 1. This comprises the business of today for the aerospace, automotive and electronics industry.

Chapter 2: Strategic Product Planning, comprising future scenarios and future applications

The second chapter outlines the Strategic Product Planing for AM-technologies for the aerospace, automotive and electronics industry, as these were identified to be the most auspicious application fields for AM. This encompasses the business of tomorrow in terms of the developed future scenarios (work package 1) and future applications (work package 2). First, the selected reference scenarios for the aircraft and automotive production, and the electronics manufacturing equipment are presented. In addition, scenarios for the global environment, comprising statements on conceivable developments of economy, politics, society and environment, are outlined. Secondly, future applications that were developed against the background of the future scenarios are presented, and requirements on DM-technologies are deduced.

Chapter 3: Strategic Technology Planning, including future requirements and innovation raodmapping

The third chapter comprises the validation of these requirements (work package 2 and 3). To ascertain the most necessary technological advancements that are compliant with the deduced requirements, two expert surveys were conducted. Initially, the requirements’ current and future significance as well as the performance of selected technologies regarding these requirements were validated. As part of the second expert survey on advancements of Direct Manufacturing technologies, a sound overview of the point in time was created, when – from AM-experts’ point of view – the selected requirements will be fulfilled by selected AM-technologies. This allows the creation of innovation roadmaps, indicating when the identified technology and material-specific as well as general requirements will be fulfilled. Taking this path, the study gives hints for increasing the success of AM-technologies and for their advancement towards DM.

Chapter 4: Conclusion and Outlook on further research

The study concludes with a summary of the project’s results. It also provides an outlook on further investigations about the future of Additive Manufacturing that the Heinz Nixdorf Institute and the Direct Manufacturing Research Center perform in collaboration.

Participating Companies/Institutions

- Benteler International AG
- Blue Production GmbH & Co. KG
- BMW AG
- The BOEING Company Corp.
- Direct Manufacturing Research Center (DMRC)
- Eisenhuth GmbH & Co. KG
- EOS – Electro Optical Systems GmbH
- Evonik Degussa GmbH
- Harvest Technologies Corp.
- Heinz Nixdorf Institute, University of Paderborn
- Honda Motor Co., Ltd.
- Huntsman Advanced Materials GmbH
- Met-L-Flo Inc.
- microTEC GmbH
- Paramount Industries, Inc.
- PHOENIX CONTACT GmbH & Co. KG
- RMB Products, Inc.
- Siemens AG
- SLM Solutions GmbH
- Stratasys, Inc.
- Stükerjürgen Aerospace Composites GmbH & Co. KG
- UNITY AG
- University of Louisville
- University of Paderborn
- University of Siegen
- Weidmüller Interface GmbH & Co. KG
- Witte Automotive GmbH

Reading Instructions

The present study allows a quick understanding. For a fast overview of the content it is sufficient to have a look at the figures and to read the summarized core statements in the marginalia. Each (sub-)chapter ends with a summary. A short description regarding the methodological approach is provided at the beginning of each chapter.

Management Summary

The present study yields an overview of the results of the project "Opportunities and Barriers of Direct Manufacturing Technologies for the Aerospace Industry and adapted others", comprising three elements: *Additive Manufacturing Business* and the symbiotic incorporation of *Strategic Product Planning* and *Strategic Technology Planning*.

The Additive Manufacturing (AM) business gives a concise overview of the development of AM-technologies, the current characteristics of selected technologies, and today's business of AM in the aerospace, automotive and electronics industry. This shows up the current market penetration of AM. Strategic Product Planning supports the identification of potentials for the business of tomorrow in the mentioned industries. Using conclusive scenarios as an environment for the business of tomorrow, promising ideas for potential applications are developed. These in turn automatically set requirements on AM-technologies in the future. Strategic technology planning supports the anticipation of the technologies' future potential and deduces required technological advancements. This allows bridging the gap between the market and technology perspective which enables the AM-industry to be prepared for the business of tomorrow and to bundle available competencies for demand-oriented technology strategies. Taking this path, the study gives hints for increasing the success of AM-technologies and for their advancement towards Direct Manufacturing (DM).

The Business of Additive Manufacturing

The awareness for AM's potentials is growing; many industries are seeking for ways to exploit them.

The analysis of today's AM-business indicates that AM is swiftly growing in significance for many industries as it offers great possibilities to accelerate innovation, compress supply chains, reduce material and energy usage, and waste. A lot of industries are seeking for opportunities how to capitalize on the benefits AM provides, e.g. the "Freedom of Design". New industries progressively draw their attention to AM's potential.

The aerospace, automotive and electronics industry were identified as auspicious for the future AM-business.

In particular the aerospace industry, which produces geometrically complex high-tech parts in small lot sizes, can benefit from AM's ability to simultaneously reduce material consumption, and easily create aircraft parts with complex internal structures. Therefore, already today the aerospace industry is in the vanguard of the industrial application of AM. Progressively, AM also holds great promise for the automotive and electronics industry. For instance, vehicle and engines components could be realized using fewer parts and rapidly redesigned to minimize failures. The aerospace, automotive and electronics industry were identified to be promising for the future AM-business.

Strategic Product Planning

To delineate future prospects and threats for possible beneficiaries of AM in the tree outlined industries, both, branch scenarios, and scenarios for the global environment were developed.

Future aircraft production: Individual customization requires ground rules for secondary aircraft structures.

The selected reference scenario for the aerospace industry – the most probable scenario with the highest effect on the future aircraft production – describes a future, where with regard to the global environment Europe sets the pace in a globalized world. The future aircraft production is characterized by individual customization of aircraft which fosters the application of AM-technologies. In this world, many manufacturers jumped on board and have been increasing their investments into AM-technologies. Due to the successful part implementation, AM-parts started to be associated with high performance and high quality. Success in this future necessitates general ground rules for the design of secondary aircraft structures, systems etc. for AM-technologies that need to be flowed down to suppliers.

Future automotive production: New concepts and individuality necessitate higher AM-productivity and quality.

In the selected reference scenario for the automotive industry, the future automotive production is characterized by new production concepts that drive individuality of automotives. Further research has provided substantial improvements of AM-processes. Thus, AM in series production is possible by now. Functional-driven design is the key to its success. Against this background, it is necessary to increase the productivity and the quality of AM-parts.

Future of manufacturing equipment: Individualized production requires qualified AM-processes and materials.

In the future of the electronics manufacturing equipment, highly integrated production systems for individualized production prevail. Networks between global and regional operating manufacturers have been evolving: manufacturers are strongly cross-linked, as value-added networking has been proven as an appropriate method to mutually increase competencies. To succeed in a future that is characterized by highly integrated production, the production has to incorporate AM.

27 innovation fields, comprising 120 ideas, were identified.

The mentioned scenarios were used as an impulse to develop ideas for future applications of DM. The spectrum of the identified applications encompasses 120 ideas. These were clustered to 27 innovation fields and prioritized based on the assessment of their chances and risks. The most promising innovation fields were concretized in specific expert workshops as well as through market research.

For the aerospace industry, *Morphing Structures* and *Multifunctional Structures* were assessed to be the most auspicious innovation fields for the application of DM.

- **Morphing Structures** describe applications which are designed as one part that is adaptable in its shape in response to its operational environment. Instead of changing the position of a static part by using actuators, the part itself can take continuous configurations of shape to enable specific functions/properties.
- **Multifunctional Structures** comprise ideas for functionally upgraded parts. Upgraded functionality can, for instance, be realized by integrating acoustic and thermal insulation into aircraft parts or by embedding entire sensor/actuator systems, including electronic wiring and connectors into a part. This can contribute to realize self-optimizing parts.

In the automotive industry, the innovation fields *Handling of Fluids* and *Optimized Tooling* were assessed to entail the greatest potential for DM in the future.

- **Handling of Fluids** yields an overview of parts that focus on geometric adaption of pipes, valves, restrictors etc. to individual purposes. Depending on their application, these parts have to be improved, for example with regard to optimized exchange of thermal energy and gas distribution, critical strength properties, weight or space reduction.

- **Optimized Tooling** includes the integration of channels into tooling parts to improve durability and resistance of tools. By applying AM-technologies, a more flexible way of arranging cooling channels can be achieved, as cross-sections of cooling channels can take any arbitrary shape. Thereby, uniform heat dissipation and quicker cooling processes can be reached.

The innovation fields *Functionally Integrated Parts* and *Testing Systems* were selected as the most promising innovation fields for the application of DM in the electronics industry.

- **Functionally Integrated Parts** include application ideas which focus on embedding electronics (circuits) into all kind of geometries and on functional integration of different electronic devices into a single part, following the principle of the Molded Interconnect Devices (MID)-technology.

- **Testing Systems** give rise to a set of ideas around electric control cabinets or circuit board assemblies. Additively manufactured testing equipment can be produced including all required, individually arranged attachment points whereby tests could be carried out in a single step.

Most innovation fields require reliable process stability, certification, design rules and on-line control processes.

To align the technology development with current and future requirements and to effectively advance AM-technology into dependable DM-technology, the developed innovation fields were analyzed in detail to deduce requirements. The range of requirements covers technology and material-specific as well as general requirements. The vast majority of innovation fields necessitate a high process stability, certification, design rules and processes for the control of part quality during the production process, just to name a few.

Strategic Technology Planning

The requirements' significance and performance of AM-technologies were validated in a survey.

In a subsequent step, the requirements deduced from the innovation fields were validated in an expert survey to identify the most important requirements and the performance of selected AM-technologies concerning these requirements. The overall assessment of the requirements shows that their significance will increase in the future. Outstanding requirements for the penetration of AM in the future are:

- High process stability,
- A database containing properties of AM-materials,
- On-line quality control processes,
- Continuous certification and
- Availability of design rules.

Large deviations between the current and future significance arise for:

- Ability of AM-machines to process different types of materials within one job,
- Building up on 3-D surfaces,
- Provision of additively processible shape memory alloys,
- Automated integration of AM-machines into existing production lines,
- Highly integrated AM-machines.

However, although some requirements play a significant role for the realization of many applications, the experts only attach a subordinate significance to those. For instance, a large number of applications ideas from the aerospace or automotive industry, such as *Morphing Structures* or *Functional Body-in-White*, respectively, necessitate AM-machines with large build chamber volumes. The experts however do not expect a build chamber volume sized larger than 8 m³ to be relevant in the future.

Today: AM-technologies' performances largely correlate with the requirements' significance.

Future: Fundamental, technological advancements are required to meet future requirements.

The technologies' degree of performance largely correlates with the requirements' significance today. However, the experts expect that the vast majority of the requirements will gain in significance. Hence, if the technologies' performance will not be advanced, these requirements will turn into critical requirements. Some requirements, e.g. build-up rates > 100 cm³/h, are already considered as critical today. These requirements indicate required research areas, as these could promote AM-technologies in the future. The amount of research required to meet a requirement sufficiently strongly depends on the requirement itself as well as on the technology. For instance, an adequate availability of self-healing properties requires more effort in development than increasing process stability to a sufficient level; high process stability necessitates less research effort for powder bed fusion plastic technologies than for corresponding metal technologies.

Material-specific and general requirements are expected to be met faster than technology-related requirements.

The innovation roadmapping of required advancements indicates the experts' assessment on the point in time when the selected requirements are expected to be fulfilled by selected AM-technologies. The overall assessment shows that advancements on fulfilling the technology-specific requirements are expected to require higher effort than the fulfillment of material-specific and general requirements. For instance, a database containing material properties and design rules are assumed to be available before 2016. In contrast, AM-machines with a significantly larger build chamber volume and higher build-up rates are expected to become available in 2025 at the earliest.

Innovation roadmaps: Sophisticated tool for strategic product and technology planning

The innovation roadmaps are a sophisticated tool for strategic product and technology planning, as they allow aligning the technology development with current and future requirements. Moreover in these roadmaps, conceivable future applications can be positioned orthogonally at the earliest possible realization date of the requirements that need to be fulfilled. Thereby the roadmaps indicate when the applications can be realized as the technology will have reached the required performance.

1

The Additive Manufacturing Business

The study “Thinking Ahead the Future of Additive Manufacturing – Analysis of Promising Industries” analyzes 14 current application fields from market and technology perspective in the context of AM, see [GEK+11]. Based on this, the aerospace, automotive and electronics industry were outlined as particularly auspicious for the business of tomorrow. This chapter provides an overview of the current AM-business. Chapter 1.1 outlines the development of AM from its beginning until now. Chapter 1.2 yields an overview of selected AM-technologies that were particularly focused in the project. Chapter 1.3 comprises an analysis of the aerospace, automotive and electronics industry regarding the penetration by AM today.

1.1 What is Additive Manufacturing – Development of its Beginning until now

AM is the layer-wise creation of parts.

Additive Manufacturing (AM) technologies refer to a group of technologies that build physical objects from Computer Aided Design (CAD) data. Contrary to conventional subtractive manufacturing technologies, e.g. cutting, lathing, turning, milling and machining, a part is created by the consecutive addition of liquids, sheet or powdered materials in ultra-thin layers. The geometrical and structural complexity of additively manufactured parts is limited by almost nothing but the used CAD-model. Enabling the production of individually shaped parts whose production previously was inconceivable, AM is in the clear technological vanguard when it comes to “Freedom of Design” already today. In the 14 page article “The third industrial revolution” by The Economist, AM is promoted as the production technology of the future, uniting individuality and mass production. AM is regarded as a nascent technology entailing great disruptive potential, triggering a revolution of product development processes in various industries, and enabling value creation for new business models, new products and new supply chains [Eco12].

Layer bonding by laser sintering, laser melting, laser solidification or by thermal fusion

AM-technologies can be differentiated into two groups: laser-based and nozzle-based technologies. Laser-based processes, e.g. Selective Laser Sintering, employ the principle of layer-wise solidification by applying energy via laser. Individual, thin layers of metal, plastic or sand powder are bonded with previous layers by laser sintering, laser melting or laser light solidification. In nozzle-based processes, e.g. Fused Deposition Modeling (FDM), wire-shaped thermoplastics are partly melted and extruded in the nozzle. The nozzle moves to produce the profile of the part. Due to the thermal fusion, the material bonds with the layer beneath and solidifies [Gep07], [Gri03-ol].

Stereolithographie and Selective Laser Sintering were the first AM-processes.

Stereolithography and Laser Sintering laid the foundation for AM in the 1980s. At an early stage, AM-technologies have been used to quickly create physical prototypes using resins and polymers. The term “Rapid Prototyping” refers to this kind of applications. Today AM-technologies are still used in product design and development processes in order to create haptic models and functional prototypes for checking form, fit and function. Progressively, AM finds its way into the production of end-use parts in many industries. The following sections first present characteristics of selected AM-technologies. Secondly, today’s AM-business is briefly outlined and AM’s penetration in the aerospace, automotive and electronics industry is presented.

1.2 Inventory on Selected Additive Manufacturing Technologies

This section briefly describes four categories of AM-technologies: Fused Layer Modeling, Powder Bed Fusion Plastic and Metal as well as Polymerization Technologies. For each category an exemplary technology is characterized in detail, providing technical and material data as well as a description of the process principle.

1.2.1 Fused Layer Modeling Technologies

Fused Layer Modeling (FLM) is an additive technique using a thermoplastic material. An extrusion head selectively deposits the molten thermoplastic filament to create each layer with a particular tool path. Through thermal fusion, the material bonds with the layer beneath and solidifies, thus forming a permanent bond between two layers. Directly after the deposition the material hardens [AST12]. Fused Deposition Modeling (FDM) by Stratasys, Inc. is one example for FLM Technologies [Str13b-ol]. The principle of the process is visualized in figure 1-1. Figure 1-2 presents the characteristics of FDM, specifying process and material data. For more information see [Str11b-ol], [Alp13a-ol], [Str11c-ol], [GRS10], [Geb12]. The technical and material data refer to the Stratasys FORTUS 400mc system [Str09a-ol].

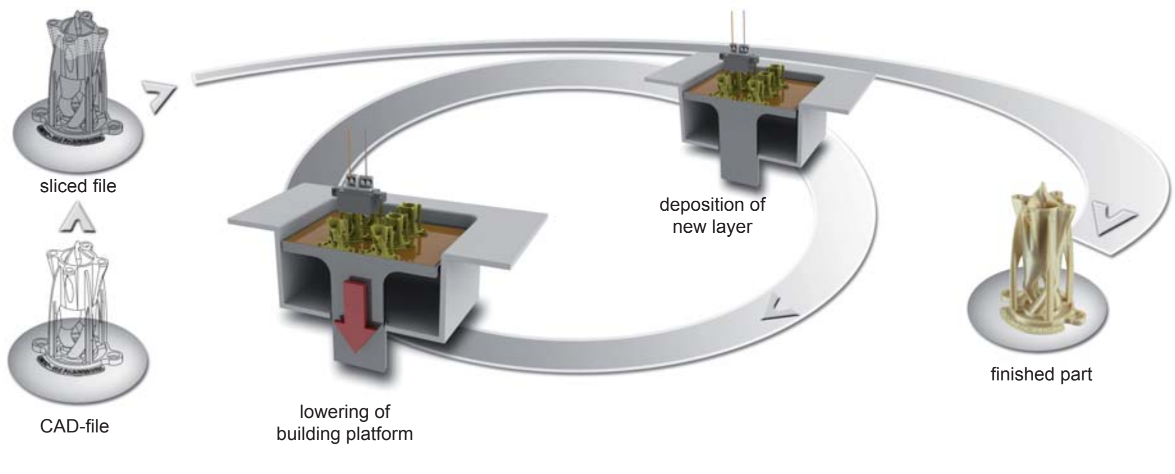


Figure 1-1: Process principle of Fused Deposition Modeling (picture courtesy of DMRC)

Fused Deposition Modeling (FDM)

Short Description

Fused Deposition Modeling (FDM) is one of the most used AM-processes and has been developed by Stratasys. It belongs to the category of extrusion-based processes that use production-grade, wire-shaped thermoplastic material. The material is melted and selectively deposited through a heated nozzle layer by layer. FDM is commercialized since 1991. Currently, the development focuses on new materials and material properties.

Technical Data*

Accuracy: +/- 127 μm

Support structures: necessary

Building speed: material and parameter dependent

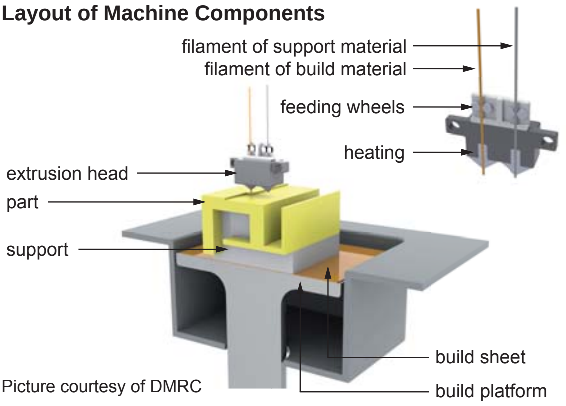
Build Materials

Material	Layer thickness
ABS	127 - 330 μm
PC-ABS	127 - 330 μm
PC	178 - 330 μm
PPSF/PPSU	178 - 254 μm
Ultem*9085	178 - 254 μm

Principle of Layer Generation

The FDM process uses wire-shaped thermoplastics furled on cartridges when delivered. In the machine, the material is partly melted and extruded in the nozzle. The material is applied to the building board directly from 3D-CAD data. The nozzle moves to produce a profile of the part. The nozzle moves in x- and y-direction; the building board moves in z-direction. Due to the thermal fusion, the material bonds with the layer beneath and solidifies. Thus, a permanent bonding of two layers is formed. When the layer is finished, the building board is lowered and the next layer is built on top. As the material hardens very fast, the complete model requires no further hardening. FDM needs a support structure for forming a base; especially for complex models with overhangs, two extrusion heads are often used. At the interface with the part a solid layer of support material is applied. Under this layer, roads with 0.5 mm and gaps with 3.8 mm are deposited.

Layout of Machine Components



Picture courtesy of DMRC

Build Chamber Volume

The spectrum of FDM machines is wide ranging from small, low-cost machines to larger, more expensive machines that are adaptable and highly sophisticated. The FDM Maxum has the biggest build chamber volume measuring (x/y/z in mm) 600/500/600 mm.

Build Time and Build-up Rate

The build time heavily depends on the amount of material in the part, the support material volume and build-up rate. The build-up rate is a function of layer thickness, road width and nozzle diameter. In general, manufacturers indicate the build time to be 25-70% higher than for Stereolithography and Laser Sintering processes. Using Ultem 9085 with a T16 nozzle, 61 cm^3/h can be produced.

Surface Quality and Accuracy

The surface quality is a function of the road width and layer thickness. As the contours of the passes of the extrusion and the single layers are still visible at the top, the bottom and the walls, FDM parts have the highest roughness. For instance, parts fabricated on the FDM Maxum using 0.18 mm layers show a roughness of Ra = 12-14 μm. At a maximum part length of 127 mm, all available machines and materials are set to reach a precision of ±0,127 mm. For bigger parts the accuracy is set to be 0.1% (but at least 0.1 mm). According to the manufacturers' specifications, the accuracy varies depending on the machine: for instance, the average deviation of the FDM Maxum amounts to 0.37%; 0.6% are indicated for the Prodigy Plus. The accuracy of the FDM process is influenced by fewer variables in total than the accuracy of comparable processes, e.g. Laser Sintering.

Material

Build Material: A wide spectrum of advanced materials, providing special properties are available for being processed by FDM. ABS (acrylonitrile butadiene styrene) is the most used material; nearly 90% of all FDM prototypes are made of this material. Derivatives of the ABS, e.g. ABSplus and ABSi, are significantly stronger, translucent and available in different colors. These materials are widely used for medical and automotive applications. Polycarbonates (PC, PC-ISO) are applicable under greater forces and loads than ABS. New, high-performance plastic polyphenylsulfone (PPSU) are characterized by high heat and chemical resistance, and are more solid and stiffer. In general, parts produced by FDM are applicable at high heat, in caustic chemicals, sterilization and under intense mechanical stresses. Elastomer and wax are further materials used for FDM.

Support Material: The so called break away support structures (BASS) and the water-soluble support structures (Water Works) are applied as support material that can be broken off or dissolved in water, respectively. As mechanical removal becomes obsolete using Water Works, it is especially suitable for small parts or for parts with regions that are difficult to access.

Data Format/Software

The software for reading the STL-files and controlling the FDM machines is "Insight". The model is oriented and mathematically sliced into horizontal layers. A support structure is created where needed. The program calculates the path of extrusion and supports the optimization of the building process. It features an estimation of the building time and optimizes the production process.

Post-Processing

No post-run operations are required in general, except the removal of support structures. BASS support structure is a brittle material to be removed without using any tools. Water Works dissolves in water. Machining/sanding is applied to reduce surface roughness.

* Technical data refer to Stratasys FORTUS 400mc by Stratasys, Inc

Figure 1-2: Characteristics of Fused Deposition Modeling

Using FDM technology, three dimensional objects of any shape can be built without restrictions on forming tools. The greatest advantages of the FDM process are the relative simplicity of the process and the availability of different materials. As the material is provided on spools, material changes can be made easily and no material loss occurs during the process. Parts are built with an accuracy of +/- 127 µm and with only little warpage. The production time primarily depends on the volume of the parts to be fabricated. Due to the extrusion of the material, a seam line between layers exists resulting in parts having anisotropic properties. Most geometries require supports which have to be removed in a post process [Str13a-ol], [Str13b-ol] [Alp13a-ol], [Str11c-ol], [Str09a-ol].

FDM has found its way into the production of many industries.

FDM technology is widely used for concept models and functional prototypes, but also for end-use parts and manufacturing tools within the aerospace, defense, automotive, medical industry, as well as business and industrial equipment, education, architecture and consumer-products. End-use parts and manufacturing tools – such as jigs, fixtures and tooling masters – are produced in low-volume production [Str11b-ol]. Current research initiatives aim at better understanding the material, process and part properties. However, the research intensity in FDM technology is comparatively low [GPW13].

1.2.2 Powder Bed Fusion Plastic Technologies

Powder Bed Fusion Plastic technologies represent an additive manufacturing technique in which powdered plastic materials are selectively sintered. The energy to locally fuse the powder is performed by a laser beam. After all layers are built, the part can be removed from the powder bed. The remaining powder is reusable for future production builds after being blended with new powder [AST12]. An exemplary technology is Laser Sintering (LS) by EOS GmbH Electro Optical Systems [Eos13a-ol]. The process principle of LS is visualized in figure 1-3. Figure 1-4 presents the characteristics of the LS technology, specifying process and material data [Eos12-ol], [Eos13a-ol], [Eos13b-ol], [Eos13c-ol], [Eos13d-ol], [GRS10], [Geb12]. The data refers to the EOSINT P395.

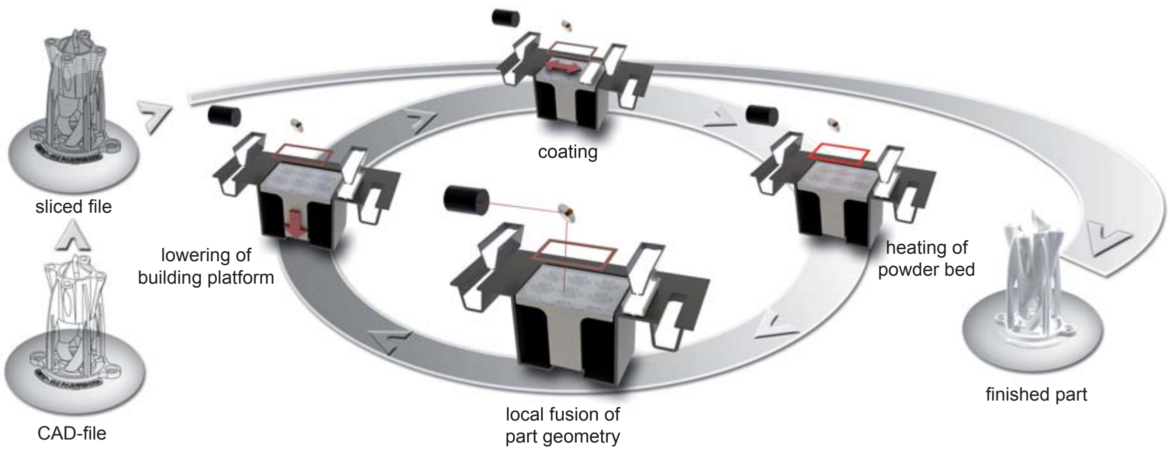


Figure 1-3: Process principle of Laser Sintering (picture courtesy of DMRC)

Laser Sintering (LS)

Short Description

Laser Sintering (LS) is an AM-process for the layer-wise creation of parts from powdered material. The manufacturing process is supplied directly from the electronic data. A laser is used to scan the layer and to fuse the powder particles to the rest of the part without melting (solid state) at elevated temperatures. Using this process, it is possible to create highly complex and individual geometries in a flexible and cost-effective way.

Technical Data*

Layer thickness: 60-180 µm

Laser type: 50 W CO_2 Laser

Scanning speed: 6000 mm/s

Support structures: not necessary

Building speed: 35 mm/h

Build Materials*

e.g. PA2200 (basis: nylon 12)

Melting temp.: ≈ 186 °C

Recrystallis. temp.: ≈ 140 °C

Particle size $d_{V,50}$: ≈ 55 µm

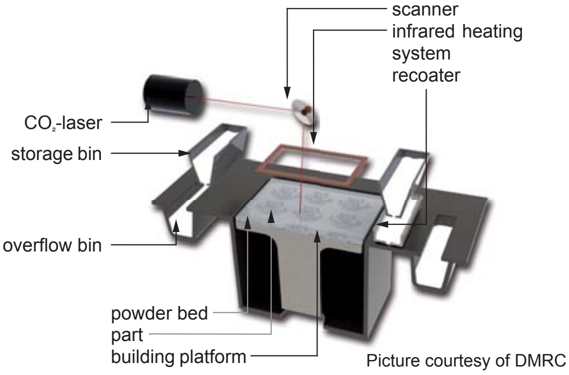
Part. size distrib.: ≈ 3-100 µm

Tensile strength: 48 N/mm^2

Principle of Layer Generation

LS (solid state sintering) machines lay down a thin layer of plastic powder. With a laser, the powder is heated up to fuse the powder with the previous layers. The fundamental difference between LS and Laser Melting (LM) is the way the powder particles are bound to each other. In LM processes, the particles are exposed to higher amount of energy. Due to the intensity of the laser, the powder particles liquefy to the state of melt and solidify in a new shape. LS processes, in turn, bake the particles together by only fusing powder particles in their “solid state”, at between one half of the absolute melting temperature and the melting temperature, but without melting the particles. After the laser has finished tracing one cross-section of the model, a new load of powder is applied on top and the process repeats. As LS requires a precise temperature control, the scanning strategy and laser energy-input have to be carefully controlled throughout the process.

Layout of Machine Components



Picture courtesy of DMRC

Build Chamber Volume

The build chamber volume depends on the size of the machine. With the EOSINT P395, it is possible to build parts with a volume of (x/y/z in mm) 350x350x620. Other machines provide up to 700x380x580 (EOSINT P760) or 720x500x450 (EOSINT P760).

Build Time and Build-up Rate

The build time depends on the part size and the machine itself. Furthermore, machines usually offer different operating modes with different accuracies and build-up rates. In most cases, it is possible to build parts with a speed of approximately 20 to 31 mm/h. For example, the EOSINT P395 and P800 can produce parts with a speed of 35 and 31 mm/h, respectively.

Surface Quality and Accuracy

Surface quality and accuracy depend on the powder and the machine itself; both are function of different process parameters, e.g. powder shape, size and size distribution, powder bed density and powder spreading. These parameters strongly influence laser absorption. Typical layer thicknesses range from 60 to 200 µm. With the EOSINT P 395, for instance, it is possible to produce parts with layers between 60 and 180 µm. Thereby, the thickness can be adjusted in five different levels at the machine. Newer machines, e.g. the Sinterstation SPro140 by 3D Systems Corp., process parts with layer thicknesses between 100 and 200 µm. Common achievable tolerances are ±0.1 mm up to ±0.5 mm. EOS provides so called PartPropertyProfiles (PPP) for their systems for specific adjustments and changes in process parameters depending on the desired properties of the final part.

Material

The spectrum of materials is exceptionally wide for LS plastic machines. Mostly, it is not limited by the process itself, but rather by the industrial demand. In general, plastic, metal and sand powders can be used in the LS process. For processable metal materials see the characteristics of Selective Laser Melting. Common plastic powders consist of Alumide, CarbonMide, different Polyamides and Polystyrenes. Known products are GF, HST10, AF, Duraform PA, Duraform GF, Duraform HST10, Duraform EX and Duraform PP. These materials are custom-made polymers that suit the industrial demand in different fields requiring specific properties, e.g. fire or acid resistance. High-performance polymers for the LS process, e.g. PEEK HP3 (based on Polyaryletherketone – PAEK), are suitable for applications that require excellent high temperature performance, wear and chemical resistance etc. The parameters of this material are on an up to 100% higher level compared to the so far market dominating materials PA12 and PA11. For the Sand Laser Sintering systems different ceramics or quarry sands can be used. They usually contain binding materials (<10%) and are used to produce sand molds for castings.

Data Format/Software

A 3D-CAD file is analyzed and sliced into layers varying from 20 to 100 µm in height. Each layer is saved as a 2D image using the STL file format. EOS offers a suite of tools for processing STL files. It is called EOS RP-Tools and is capable of reading STL, creating support structures where needed and positioning the part in the build chamber. The software itself is called PSW and controls accuracy, part quality, speed and other process parameters.

Post-Processing

The parts have to cool down slowly due to the high temperatures during the production process. The remaining powder has to be removed, usually by compressed air. Surface quality and accuracy heavily depend on the process parameters of reworking.

* Technical data refer to EOSINT P395; material data to PA2200 by EOS GmbH Electro Optical Systems

Figure 1-4: Characteristics of Laser Sintering

LS is used for prototyping and end-used parts in many industries.

Via LS, three dimensional objects of any shape can be built without restrictions on forming tools. Parts can have integrated functions like moving elements or inner structures. Ideal applications for LS are highly complex parts in low-volume production. LS technology is used for manufacturing prototypes, models and end-use products. Due to the huge variety of materials, the method is predestined to be used in the tooling industry, aerospace industry, automotive industry, architecture, and in the consumer goods industry. Advancements in the processing of bio-compatible, high-performance materials recently gave rise to a number of new applications, especially in the medical industry [Eos13a-ol].

The main challenges today are the optimization of part quality and repeatability of the LS process. To increase process knowledge and to optimize the process, investigations of mechanical properties, material quality and surface finish of LS parts are mandatory [Eos13a-ol], [Eos13b-ol], [GPW13]. Special attention is required to the material properties: these properties can vary depending on how many times the material has been recycled [GRS10].

Research initiatives focus material properties and processing.

Current research initiatives focus the analysis of material properties and material processing in order to realize the required property profiles. In particular, many institutes focus the analysis of monomer molecules and investigation of powder generation processes [GPW13].

1.2.3 Powder Bed Fusion Metal Technologies

Using Powder Bed Fusion Metal Technologies, powdered metal material is selectively melted layer by layer via lasers or electron beams. In the process, the powder bed fuses through solidification [AST12], [GRS10]. Selective Laser Melting (SLM) by SLM Solutions GmbH is one example for Powder Bed Fusion Metal Technologies [Slm13a-ol]. Figure 1-5 illustrates the principle of the SLM process; figure 1-6 presents the characteristics, specifying process and material data. The data refer to the SLM Solutions 250HL system. For more information see [Slm13a-ol], [Slm13b-ol], [Slm13c-ol], [GRS10], [Geb12].

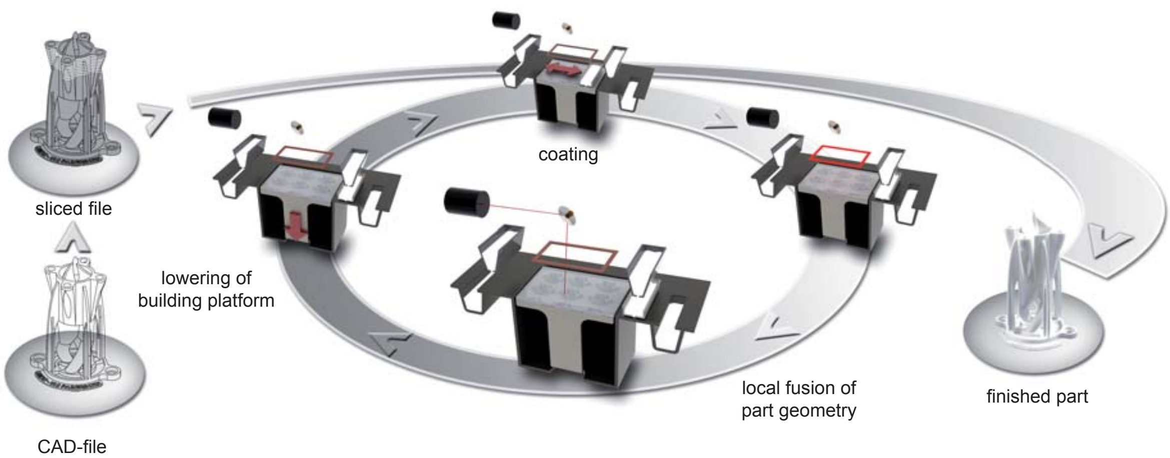


Figure 1-5: Process principle of Selective Laser Melting (picture courtesy of DMRC)

Selective Laser Melting (SLM)

Short Description
Selective Laser Melting (SLM) is a process that creates three dimensional parts by fusing fine metallic powders together. The process uses a high powered Ytterbium fiber laser to fuse the powder; the metal is fully melted into a solid homogeneous mass. The technology was invented by F&S – Stereolithographietechnik GmbH and the Fraunhofer ILT. The popularity of metal-based processes is growing.

Technical Data*
Layer thickness: 20-100 μm

Laser type: Ytterbium laser 400/1000 Watt

Scanning speed: 20000 mm/s

Support structures: necessary

Bulding speed: 25 cm^3/h

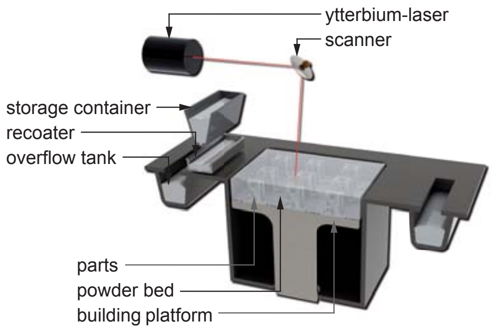
Build Materials
Titanium, Aluminium

Tool/Stainless steel

Alloys depending on the application

Typical tensile stress values: 400-1200 N/mm^2

Principle of Layer Generation
SLM uses fine metal powders to build a part layer by layer. The process is executed under a closed atmosphere of shielding gas in order to achieve maximum part quality. First, a layer of powder is placed on the building platform. The ytterbium laser traces the cross section of the part, thereby fluidizing and melting the respective particles (> melting temperature) together. The remaining powder serves as additional support structures. Upon completion of one cross-section, the platform is lowered by the height of one layer and another load of raw material is placed upon the existing model. Each time the laser liquefies a new layer of powder, both, the existing material and the raw material melt and a new shape is generated. This procedure is repeated until the part is finished.

Layout of Machine Components


Picture courtesy of DMRC

Build Chamber Volume
The SLM 500 HL system by SLM Solutions GmbH offers a build chamber sized (x/y/z in mm) 500x280x325, followed by SLM 250 with a volume of 250x250x300. The processing area can be exploited optimally by stacking pieces on top or next to each other.

Build Time and Build-up Rate
The build time depends on the layer thickness and the processed material. With finer layers, more accurate parts can be produced; higher layers however require stronger laser modules. On average, build times are 7-30 cm^3/h for SLM. In general powder bed fusion processes take longer for part construction than other AM-processes due to the pre-heat and cool-down cycles involved.

Surface Quality and Accuracy
The surface quality is a function of the layer thickness, powder shape and size as well. Finer particles form a larger surface area and absorb laser energy more efficient than coarse particles. To achieve the best trade-off between dimensional accuracy, surface quality, build-up rate and mechanical properties, temperature of the powder bed, laser power, scan speed and scan spacing must be optimally aligned. Thanks to the focused high power beam, parts with a density of over 95% can be built. The minimal layer thickness is about 20 μm. With SLM machines layer thicknesses of 25 μm and surface finishes about $R_a = 5$ μm can be realized.

Material
Processing Material: A huge variety of metal powders are already available for both processes. In order to be processable, the grains should be round and their diameter should be between 10 and 45 μm. The used alloys are free of binders or other additives. In general, almost all metals can be processed with SLM. Tool steel H13, stainless steel 316 L, Titan TiV4, Titan, Cobalt Chrome, Inconel, Aluminum and Gold are materials which are approved for SLM processes. If the process parameters for a special material have not been standardized yet, manufacturers offer to develop the corresponding work specifications in cooperation with the customer.

Support Material: The support structure is needed to absorb the occurring stresses during the building process. The support structure is built from the same material as the part, and is removed after production.

Data Format/Software
A 3D-CAD file is sliced into layers varying from 20 to 100 μm in thickness. Every layer is saved as a 2D image in the STL format. The machine control software reads these files and creates support structures where needed. It also determines the building orientation and controls all process parameters. The system offers the software Magic AutoFab for processing CAD/STL-data files. It is also used for slicing and support generation.

Post-Processing
Ordinary post processing steps are support material removal, shot peening and polishing. As parts built by SLM are comparable to conventionally built parts, they can be reworked the same way, including machining, welding, eroding, etc.

* Technical data refer to SLM Solutions 250HL

Figure 1-6: Characteristics of Selective Laser Melting

SLM is widely used for light-weight structures.

Unlike machined parts, SLM parts can have thin walls, deep cavities or hidden channels. Parts with high toughness, high strength and good thermal conductivity can be produced. As the weight of the part is heavy and the heat has to be dissipated, support structures are necessary. High thermal gradients can lead to residual stress or to the cracking/failure of the part [GRS10], [Geb12]. SLM technology is used for functional testing of production quality prototypes as well as for manufacturing of complex end-use parts in low-volume, and for building highly complex organic structures. In addition, SLM is broadly applied to produce light-weight and lattice structures. Due to the technology's inherent geometric complexity benefits and excellent material properties, many industries have been benefiting from this technology, e.g. the automotive, aerospace, tooling, jewelry and the medical industry [Ren13-ol], [Rea11-ol] [Slm13d-ol].

Current research initiatives aim at the development of new materials as well as understanding and advancement of existing materials. This also comprises the analysis of material properties and material processing in order to realize required property profiles, facilitating the production and processing of industrial materials. In addition, great efforts are done to standardize part construction and to extend knowledge about potential product technologies, e.g. lattice structures, gradient structures etc. [GPW13].

1.2.4 Polymerization Technologies

Polymerization is an additive technique used to produce parts from photopolymer materials. The photopolymer material is in a liquid state. By using a laser beam the material is curing or solidifying layer by layer. The process can harden the material in a predetermined thickness. Stereolithography (SLA) is one example for Polymerization Technologies [AST12]. Figure 1-7 illustrates the process principle of SLA technologies; the characteristics, specifying process and material data are presented in figure 1-8. The data refer to the iPro 9000XL SLA Center by 3D Systems Corporation. For more information see [3ds13a-ol], [3ds13b-ol], [3ds13c-ol], [Alp13b-ol], [CCD+11-ol], [Par13-ol].

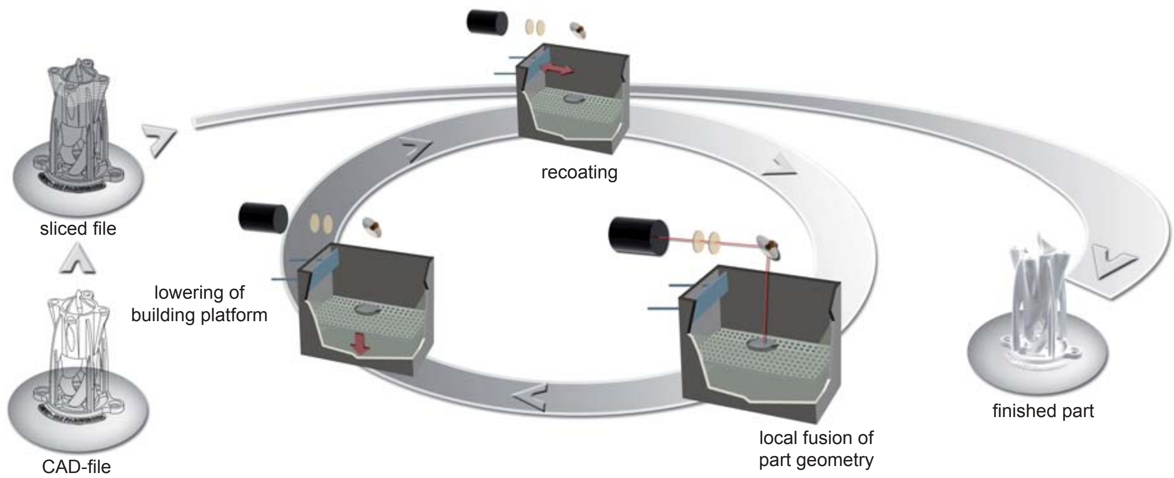


Figure 1-7: Process principle of Stereolithography (picture courtesy of DMRC)

Stereolithography (SLA)

Short Description

Stereolithography is an AM-technology using an Ultra Violet (UV)-laser to solidify liquid, radiation curable resins, or photopolymers in a basin. When exposed to UV-radiation, these materials undergo a chemical reaction to become solid. By lowering a platform in the basin layer by layer, a 3D-model is created. It is the oldest method of 3D-printing, commercialized in 1987 by 3D-Systems Corporation. Today, the technology is widely used.

Technical Data*

Laser Type: Nd:YV04

Layer thickness: 50-150 µm

Accuracy: +/- 25-50 µm

Support structures: necessary

Draw. speed: 3.5 m/sec borders); 25 m/sec (hatch)

Build Materials*

e.g. Accura ® Peak ™Amber

Liquid Density: 1.32 g/cm

Solid Density: 1.36 g/cm³

Viscosity: 605 cps

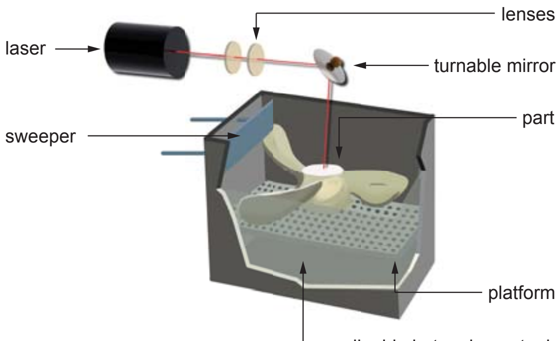
Penetration Depth: 5.6 mils

Critic. Exposure 11.5 mJ/cm²

Principle of Layer Generation

The raw material for Stereolithography is a photosensitive liquid polymer which is filled in a basin. Apart from the raw material, the basin also includes a platform that can be moved in z-direction. In its initial position, the platform is located closely below the surface of the material. A UV-laser traces the cross-section of the part, causing the first slice of the resin to solidify in the respective area. Subsequently, the platform is lowered into the resin vat by the thickness of one layer (~ 5 µm). A sweeper blade applies a new film of resin on top of the previously cured slice that is subsequently cured by the UV-laser again. This process is repeated and the following layer is fused to the solidified slice. Due to the low stability of the part during the process, support structures are required; these are also used to tie the part to the platform in order to avoid any motion of the part while the platform is lowered.

Layout of Machine Components



Picture courtesy of DMRC

Build Chamber Volume

A huge variety of SLA systems are available. Large SLA machines have vat sizes of (x/y/z in mm) 750x650x550. ProJet® MP 7000 provides a net build volume of 380x380x250; the iPro 9000XL SLA Center even has a volume of 1500x750x550.

Build Time and Build-up Rate

The build time is closely connected to the velocity of the laser which is a function of the laser power, the spot radius and the cure- and penetration depth. The build-up rate depends on the material, the amount of support structures needed and the size of the part. Compared to Laser Sintering, Stereolithography tends to be prone to longer build-up rates for bigger parts.

Surface Quality and Accuracy

Accuracy of SLA parts varies depending on build parameters, part geometry and size, part orientation and post-processing methods. However, as most epoxies used in SLA shrink by only approx. 0.1%, the process provides the highest accuracy and surface quality of all AM-processes: depending on the desired resolution, it is possible to produce parts with layers between 50 and 125 µm. The side walls show a relatively sharp and ragged contour with a roughness of 8.6 µm. Top and bottom surfaces show significantly higher surface qualities with an average roughness height of Ra = 0.3 µm at the top surface and R_a= 4.3 µm at the bottom surface. High resolution SLA systems are able to produce with tolerances of ±0.025-0.05 mm.

Material

Processing Material: Stereolithography has a limited variety of applicable materials. The quality of these materials has however significantly improved over the last years. Currently, fifteen different polymers, mostly epoxies, are available in different colors. The selection of the material depends on the application at hand, as the available materials feature different characteristics. SolidGrey3000 is an example of a material providing a high stiffness and impact resistance. Therefore it can be used for machine covers or automotive body parts. Other materials, e.g. “NanoTool”, in turn, stand out due to high heat and humidity resistance; these are mainly used for high temperature applications in the aerospace industry. 3D-Systems Corp. also offers different materials: e.g. the Accura ® Peak ™ that is a hard, accurate plastic with excellent moisture and temperature stability or the Accura ClearVue which is a plastic that resemble Polycarbonate and ABS regarding its properties and appearance. SLA machine providers usually indicate which material is suitable for which application.

Support Material: The support material usually is identical with the build material.

Data Format/Software

The majority of SLA machines use the STL format which was developed by 3D-Systems Corp. Other formats for instance are SLC, HPGL and IGES. The basic principle of all programs used for layer-based AM-processes is slicing a 3D-CAD-model into 2D-slides. Front-ends, for instance, are Lightyear by 3D-Systems Corp. or Suite by EnvisionTEC, Inc.

Post-Processing

SLA requires the manual removal of support structures which significantly determines the accuracy of parts. As only 96% of the polymer solidifies when being exposed to the laser beam, parts manufactured via SLA need to be placed in a UV oven for a final curing.

* Technical data refer to iPro 9000XL SLA Center; material data to Accura ® Peak ™Amber by 3D Systems Corporation

Figure 1-8: Characteristics of Stereolithography

SLA parts provide high accuracy and smooth surfaces. There is a great variety of materials that can be processed via SLA, mimicking the look and feel of most engineering plastics, e.g. Polypropylene, Polycarbonate and ABS. These materials provide properties like thermal resistance, stiffness, flexibility and transparency to meet prototyping, testing and application needs.

SLA technology is used in many industries.

Today, SLA parts are widely used for rapid prototyping and partly for DM in a huge variety of industries, including the medical, military, electronics, automotive and consumer goods industry. Exemplary applications are patterns for injection molding core and cavity inserts, thermoforming, sand casting, blow molding, and various metal casting processes [3ds13d-ol].

Current research initiatives focus on the development of new materials and the advancement of the laser technology to accelerate production processes [GPW13].

1.3 The Business of Today

The study “Thinking Ahead the Future of Additive Manufacturing – Analysis of Promising Industries” analyzes 14 current application fields from market and technology perspective in the context of AM, see [GEK+11]. This chapter gives a short overview of current application fields, and especially outlines today’s penetration of AM in the aerospace, automotive and electronics industry.

1.3.1 Overview

Where is AM headed today? According to Wohlers Associates, an independent consulting firm in AM, emerging trends like low-cost 3D printers are increasingly helping to create visibility for the industry, facilitating access to the technology for inventors, entrepreneurs, researchers, do-it-yourself enthusiasts, hobbyists etc. [Woh12]. With the latest advancements in machine and material development, e.g. the development of high-performance polymers, the production of final parts that fulfill the required mechanical properties becomes possible. This is Direct Manufacturing (DM).

AM-market is continuously growing.

According to Wohlers, the AM-market grew by 29.4 % amounting to $1.721 billion in 2011 [Woh12]. This includes products, e.g. AM-systems, systems upgrades, materials, and services, e.g. production and maintenance services. Wohlers Associates forecasts the industry-wide revenues to grow to $ 3.7 billion in 2015. By 2019, the revenues are expected to amount to $ 6.5 billion. The reason therefore is obvious: a growing number of industries have been and are realizing the promising potentials of AM-technologies, as shown in figure 1-9.

Aerospace industry is a pioneer in the application of AM.

In particular, the aerospace industry is in the vanguard of the industrial application of AM. Aircraft manufacturers and their suppliers, e.g. Boeing, EADS (European Aeronautic Defence and Space) or Paramount, apply AM-technologies for manufacturing geometrically complex, but reliable high-tech aircraft parts, drastically cutting down production costs and weight. Plus, AM significantly contributes to optimize the supply chain, to reduce lead times and environmental impacts, thereby adding value to the industry's business.

A broad variety of industries do already benefit from AM's potential.

AM is also widely spread among the medical sector, including dental applications, prostheses, implants etc. The technologies are also applied in the capital goods industry, e.g. in the armament, automotive and electronics industry as well as in the tool- and mold-making industry. Even the consumer goods industry, e.g. the sports, textile, furniture, toys and the jewelry industry are becoming aware of AM's great advantages for their business. AM in means of DM is not extensively prevalent yet, experts however underscore its huge potential.

Figure 1-9: Overview on industries using Additive Manufacturing [GEK+11] (pictures courtesy of: see picture credits on page 105)

AM is largely used for complex, induvidual and functionally integrated parts.

In the majority of application fields, AM is used to shape geometrically complex parts, for instance designer lamps or pendants in the jewelry industry. Within other industries, AM enables functional integration, such as double walled structures that are used in air conditioners for isolating cables [Woh11]. In the textiles and food industry, possible applications are currently being explored. Research in these areas, such as "printing food" during space missions and producing seamless garments, already shows up possible future applications [BLR09]. However, the use of AM is still limited in these industries.

Close cooperation between research and industry is crucial to qualify AM for DM.

However, companies that explore AM’s potential and develop ways to exploit these potentials can acquire a competitive edge in global markets. To tap the extraordinarily high potential and to advance materials as well as the technologies into the right direction, a close cooperation between researchers, technology suppliers and users is mandatory. This is the main purpose of the foundation of the Direct Manufacturing Research Center (DMRC). The major goal of the DMRC is to advance AM-technologies into dependable, production rugged Direct Manufacturing technology (DM).

An essential prerequisite for the successful (industrial) establishment of Direct Manufacturing will be the awareness of its fascinating capabilities and advantages among industrial operators. Concurrently, AM-technology providers have to be aware of specific customer demands and the general framework in (potential) user industries (e.g. certification processes in the aerospace industry) to optimally fulfill customer demands with the right products at the right time. This is the starting point of the project ‘’Opportunities and Barriers of Direct Manufacturing Technology within the Aerospace Industry and adapted others“, lining out opportunities and barriers of DM-technologies in the aerospace, automotive and electronics industry. These industries were analzed in detail in the study “Thinking Ahead the Future of Additive Manufacturing – Analysis of Promising Industries“. In the following, these three industries are briefly introduced.

1.3.2 Aerospace Industry

Aerial transportation has never been as important as today, and will likely play a key role in the future as well. Today, the variety of aerial vehicles is wide, ranging from unmanned aerial vehicles (UAV) and transport aircraft to vehicles for space tourism [Bul09].

Aerospace parts are generally produced in small quantities at comparatively high costs per unit, and thus are regularly operating without economies of scale. Besides this, aircraft parts have to meet a high number of requirements. Managing the high complexity of systems, concurrently responding to environmental demands and reducing operating costs are just a few challenges of the aerospace industry. An additional challenge is attributed to increasing oil prices. To confront these challenges, the aerospace industry continuously endeavors to improve performance of aircraft and to reduce air pollution, noise exposure and raw material consumption [Bul09].

AM has great potential to cope with the requirements of the aerospace industry.

Emerging technologies such as AM-technologies open up great potentials to cope with those challenges. The reason therefore is obvious. AM-technologies enable the creation of parts of any arbitrarily individual geometry which fits well to the aerospace industry’s demand for geometrically complex and strong parts. Furthermore, AM allows creating light-weight structures, massively cutting down material consumption. Due to this, the aerospace industry is a pioneer in the AM-business already today. Global players like Boeing and Airbus apply AM-technologies already; small companies are expected to follow this trend [Wor10], [Wor11a], [GEK+11], [GEK+12].

AM-market is growing in the aerospace industry.

According to a survey conducted by Wohlers Associates, the share of the aerospace industry of the global AM-market volume amounts to

12.1%, which grew from $131 million to $207 million [Woh12]. Compared to the expected world market volume of the aerospace industry (including defense) amounting to $677 billion in 2011, the AM-market share is still marginal [RE11], [PWC12-ol]. However, as parts manufactured by AM-technologies progressively meet the requirements of the aerospace industry, the range of additively manufactured products is quite diverse at present. Exemplary parts that have already been manufactured additively are:

A broad variety of AM-parts prevail in the aircraft production.

- Environmental control system ducting by Boeing [Woh12];
- Swirler – fuel injection nozzle for gas turbine applications by Morris Technologies, Inc. [Mor13-ol];
- Rotor made from, NickelAlloy IN718 by Morris Technologies, Inc. [Mor13-ol];
- EADS Innovation develops wing brackets, hinges for engine covers, air intake baffles, and aerodynamically profiled cooling ducts for Airbus with Selective Laser Sintering [Thr12-ol];
- Venturi nozzle by Morris Technologies, Inc., see figure 1-10 [Mor13-ol].

Figure 1-10: Venturi nozzle made by Direct Metal Laser Sintering (DMLS) (picture courtesy of Morris Technologies, Inc.)

- A Mars rover, containing about 70 parts made with Stratasys FDM and a production-grade Fortus printer, e.g. pod doors, large components that work as a front bumper, camera mounts, flame-retardant vents and housings [Thr12-ol];
- Thrust reverser doors and acoustic panels by Royal Engineering Composites [REC11-ol];
- Landing gears by EADS [ASA11-ol];
- Gimbal eye, or camera by Stratasys Inc. rotates electromechanically on two axes [Str11a-ol];

- In cooperation with EOS, EADS remanufactured a titanium cover door hinge for the A380. Thereby, the hinge is 65% lighter compared to a conventional hinge [Des12-ol].
- The NASA tested 3D Printing in zero gravity for using 3D Printers on the International Space Station [Des12-ol].
- In collaboration with the Advanced Manufacturing Collaborative Research Center in Australia, the manufacturer Microturbo for gas turbine jet engines, is developing Selective Laser Melting methods for producing aerospace microengine components using metal alloys [Des12-ol].

AM is expected to have disruptive changes on the aerospace industry's business.

These developments show that AM is progressively gaining ground in the aerospace industry. Especially against the background of prevalent trends, such as light-weight structures and increasing individuality of aircraft design and interior, AM is expected to enjoy record growth in the aerospace industry, having a transformative impact on the industry [Wor11a]. Therefore however, many advancements of the technology will be needed. The definition of common design rules, the establishment of certification processes for AM-parts and AM-processes etc. are critical success factors from today's point of view, just to name a few [Wor10], [GEK+11].

1.3.3 Automotive Industry

The desire for individual mobility makes the automotive industry a powerful and important market. Even after the economic crisis in 2007, the automotive industry has proven to be a pacemaker for many economies [HP11-ol].

The automotive industry has always been a highly technology- and innovation-driven industry: customer demands on design, safety and environmental performance, dynamics, variability, comfort, "infotainment", cost effectiveness and sustainability converge in a melting pot of challenges and determine which companies will prove themselves in competition [Bul09].

Penetration of AM in the automotive sector is increasing.

In order to tackle these challenges, the automotive industry is a pioneer in applying innovative technologies in many instances. This also applies to AM-technologies. In 2011, the automotive industry contributed 19.5% to the total AM-market volume which corresponds to $334 million [Woh12]. Together with the motorsports industry, the automotive industry amounts to the second largest market volume after the consumer products/electronics industry. Compared to the world-wide automotive industry market volume of $2.6 trillion, this share is still marginal [SZW11-ol].

In the automotive industry, AM has the potential to accelerate innovation processes.

The automotive industry is taking advantage of the technologies to produce plastic, metal, or composite parts and customized products. The main purpose is to reduce costs, time and tooling required in the conventional manufacturing processes and to accelerate innovation and product development processes. For instance, Stratasys FDM technology has now been used for more than twenty years for modeling and prototyping purposes, but for manufacturing end-use parts as well. Automotive manufacturers, e.g. the BMW AG, are continuously extending the field of application for AM in the use of both polymeric and metallic AM-technologies [Str09b-ol]. Luxury and antique cars manufacturers apply AM to directly produce small, complex and non-safety relevant parts. The vast majority of these parts are produced in small series, as process productivity is still limited [BLR09].

Motorsports sectors has been using AM for years.

In the motorsports sector, AM has been a linchpin for design and testing for years. Progressively, AM is applied for manufacturing parts that endure the rigors of high-speed and high-performance racing. This field largely benefits from the knowledge gained in the application of AM in the aerospace industry: especially the know-how for manufacturing complex, high-tech aerospace parts is increasingly transferred to future applications in the motorsports sector [EJN11-ol], [Str12a-ol].

Increasing number of automotive applications

Further examples for current applications in the automotive industry are listed in the following:

- Intake valve and other parts of the engine bay, gearbox and engine components by Mini John Cooper Works WRC [LL11-ol];
- Kor Ecologic developed the Urbee, an electro-hybrid vehicle: all body components were produced with Dimension 3D Printers and Fortus 3D production systems by Stratasys, as shown in figure 1-11 [Eco11-ol].

Figure 1-11: The Urbee Hybrid: the first 3-D printed car (picture courtesy of Kor Ecologic, Inc.)

- Oversized radio knob and custom hose ducting by Stewart-Haas Racing [Str12-ol];
- Air inlet, engine control unit and lower fairing baffle for ADV Racing [Woh11];
- Hand tools for automobile assembly for BMW by Stratasys Inc. [Str11b-ol];
- Gear shift knob by Materialise [Mat11-ol];
- Testing part design to verify correctness and completeness of parts by BMW, Caterpillar, Mitsubishi [BTW09], [Cev06];

- Pre-series components for luxury sport cars, e.g. intake manifolds, cylinder heads by Lamborghini [Cev06], [Fro07];
- As a foundation for light-weight automobile construction, the Daimler AG and the Fraunhofer Institute for Laser Technology in Germany developed a new laser melting machine with a larger build chamber than any previous model for aluminium alloys [Bro12-ol].
- Joe Gibbs Racing uses Stratasys FDM to create complex carbon monoxide filter housings for their NASCAR cars [Str12a-ol].

In many instances, in the automotive sector the hesitant application of AM-technologies is mostly due to the limited construction size of current AM-machines [Wor11b]. The development of AM-systems providing a bigger build chamber volume, increasing process reliability and part reproducibility, and the development of common design rules and certification processes are just a few critical success factors that are expected to influence the success of the AM-business [Wor10], [GEK+11].

1.3.4 Electronics Industry

Electronics industry is characterized by a rapid development.

The broad variety of electronics are present in daily life in many instances, e.g. in mobile phones, computers, automotives etc. Therefore, many industries are affected by the developments of the electronics industry: electronics are the enabler for many innovations and developments, as especially the electronics industry is characterized by rapid technological advancements and the continuously shortening product life cycles. To accelerate development and manufacturing processes, AM can be a promising approach. As AM enables functional integration and embedding electronics into all kind of geometries, the technology can also respond to the major trends of the electronics industry, such as miniaturization, functionally integrated (micro) systems, embedded technology, energy-saving electronics, printed electronics etc. [SI10-ol]. Combining 3D printing and printed electronic circuitry has the potential to completely streamline production processes as less material and process steps are required.

Penetration of the electronics industry by AM is increasing.

In 2011, global revenues in the electronics industry amounted to \$3 trillion, growing at a Compound Annual Growth Rate (CAGR) of approximately 10% [Hyp11-ol]. Regarding the usage of AM in the electronics industry, the market is continuously growing as a great variety of processible materials such as new polymers, and metals and inks have been emerging [SA10]. Especially, the production of manufacturing and tools equipment benefits from the deployment of AM. Here, in particular, 3D-printing is a leading technology due to the high ability to include electrical circuits into work pieces. So far, a variety of electronic parts have already been realized via AM:

- Embedding Radio Frequency Identification (RFID) Devices inside solid metallic objects [Ree09];
- Polymer based, three-dimensional micro-electromechanical systems by MEMS [FCM+08];

- Connector housings and solenoid bodies by VG Kunststofftechnik [PP11-ol];
- Microwave circuits fabricated on paper substrates [YRV+07];
- Ultrasound transducers by General Electric [GE11-ol];
- All kind of grippers within automated production systems e.g. made by Stratasys, Inc. (see fig. 1-3).

Figure 1-12: Gripper made by Fused Deposition Modeling (picture courtesy of Stratasys, Inc.)

- Stratasys and Optomec completed a joint development and created a “smart wing”, which is a printed wing with printed electronics on it. The wing is the first fully printed hybrid structure [Str12b-ol].
- Researchers at the University of Warwick created a simple and inexpensive conductive plastic composite, which can be used by low-cost 3D-printers for producing electronic devices [Woo12-ol].
- Spare parts for high-tech electronic components are increasingly produced additively [Wor11c].

In the electronics industry, success factors for increasing market penetration of AM are surface quality, process reliability and part reproducibility, new materials, just to name a few [Wor10], [GEK+11].

1.4 Summary

The outlined development of AM from its beginning until now shows that AM is increasingly gaining importance in many industries. The inventory on selected AM-technologies shows that many investments are being done to advance AM-technologies even further. New materials with outstanding properties have been and are still being developed as well as new AM-systems providing a bigger build chamber volume and being faster than their predecessors.

In the study “Thinking ahead the Future of Additive Manufacturing – Analysis of Promising Industries“ 14 industries were analyzed regarding their penetration by AM. The spectrum ranges from currently established fields, such as the dental industry, and upcoming fields, e.g. the aerospace industry, to visionary fields such as the food industry.

Aerospace, automotive and electronics industry are promising application fields for AM.

Based on the analysis of these application fields regarding their market and technology development, three industries turned out to be particularly promising for the application of AM in the future: the aerospace, automotive and electronics industry. In the present study, these industries were examined in detail. The analysis shows that the penetration of AM-technologies has continuously been increasing in these industries; however, it is still limited to small series production. From today's perspective, the most decisive success factors for the business of AM are: design rules, process reliability and part reproducibility as well as surface quality and certification processes.

2

Strategic Product Planning

For a sustainable development of companies from capital goods industries, in terms of achieving economic, social and environmental goals, technology-induced innovation is of growing importance. Technology management, especially in case of emerging technologies, is a challenging task that requires a strategic perspective: the technology development needs to be aligned with market and industry needs, now and in the future. Therefore, opportunities from technological and market developments need to be recognized timely and synchronized in a symbiotic manner. Thereby, chances and threats for the established and future business can be anticipated at an early stage, and technology providers get an idea of how the areas of application for their products may look like in the future [GPW09].

For future success, technology and market developments have to be synchronized.

Opportunities for tomorrow's business and future market demands can be identified within a systematic foresight process using the Scenario-Technique. As a result of the analysis of the today's AM-business (see chapter 1), the aerospace, automotive and electronics industry were outlined as particularly auspicious for the AM-business in the future. To delineate future prospects and threats for possible beneficiaries of AM, strategic product planning was carried out.

First, the future of the three industries was anticipated, in terms of future scenarios and future applications. Secondly, future requirements on DM were deduced [GEK+11], [GEK+12]. Chapter 2.1 briefly presents the future scenarios that were selected as reference basis, and deduces future success factors and strategic directions. Chapter 2.2 provides an overview on future applications of AM that were developed against the background of the future scenarios. In chapter 2.3, future requirements the developed applications impose on AM are presented.

For the aerospace, automotive and electronics industry, strategic product planning was performed.

2.1 Future Scenarios

The visionary insight into the future, the early identification of tomorrow's success potentials and the timely exploitation of these potentials are indispensable for sustainable business success. Using the Scenario-Technique, future branch scenarios for the aerospace, automotive and electronics industry were developed for the year 2020. The branch scenarios focus the aircraft production, automotive production and the electronics industry manufacturing equipment, respectively. However, industries do not operate as standalone players. They rather are embedded in a global environment, and thus the future scenarios are a hybrid combination of a branch and a global scenario. Therefore, the scenarios for the global environment and the branch scenarios were matched to overall scenario combinations. For each industry, a reference future scenario was

Future scenarios were developed for the selected industries.

selected. This chapter presents and illustrates the selected reference scenarios. More information on the procedure for developing scenarios is provided in the study “Thinking ahead the Future of Additive Manufacturing – Analysis of Promising Industries” [GEK+11]. A detailed description of all scenarios developed in the project is part of the confidential study that is accessible for DMRC partners only.

2.1.1 Future Global Environment

The future global environment is described by 17 key factors.

The developed global scenarios describe possible future situations of the broader environment based on 17 key factors, comprising statements on politics, economy, society and environment [GEK+11]. In total, three global scenarios were developed. One scenario was selected as reference scenario. This describes a future where **“Europe Sets the Pace in a Globalized World“**. This scenario fits with the branch scenarios selected as reference for the considered industries. Figure 2-1 visualizes this scenario.

Politics: High financial support of research institutions by the government pays off.

Increasing influence of strong governments has a major impact on the political progress within the European Union (EU). On the one hand, governments have increased the total subsidies in recent years. On the other hand, the governments commit themselves to the education and research policy, by increasing the expenses for education and research.

The investments in the educational system pay off – the research infrastructure is excellent. The broad majority of the population is well skilled; however, there is still a labor deficit. In addition, prosperity is fostered through European integration. Foreign trade is facilitated; free trade without borders is possible within the EU. Protection of technological advances is proceeding slowly.

Economy: European economy grows due to value-creation-intensive enterprises.

Due to the great image of the EU as a high-tech site, many companies use the EU as a “System Head”. Especially, future- and high-quality-oriented as well as value-creation-intensive company divisions are settled in the EU. This makes Europe a key players and pacemaker of the globalization: European states succeeded to steadily increase their exports to Asia and America. Benefiting from these developments, the EU has recovered well after the economic crisis; the gross domestic product is growing by 2% annually. This development has been stable for years.

Due to good living and working conditions in the past years, the number of immigrants has been rising continuously, whereas the number of EU inhabitants has been declining. Children and family have a high priority in society; however, there still is a birth deficit. Older people feel needed, and are willing to work longer.

Society: Strong tendency towards urbanization

Moreover, urbanization has been propagating; more than 60% of the population is living in urban areas, as cities offer a good infrastructure, a variety of attractive job possibilities. In contrast, a tendency towards a way of new country life is also discernible: more than 20% of all inhabitants live in the countryside. New decentralized working forms enable people to retreat from the urban areas and to work at home.

Figure 2-1: Visualization of the reference scenario for the global environment "Europe Sets the Pace in a Globalized World" (pictures courtesy of: see picture credits on page 105)

Society: Increasing awareness for sustainable mobility

To adjust differences in income, an unconditional basic income was introduced by law: the governments pay every inhabitant this basic income without any repayment claims. Additionally, the awareness for highly sustainable mobility has been emerging which has been leading to a boom of the ecologically reasonable means of transportation. Due to this development and to the availability of modern digital forms of communication, new virtual mobility is propagating increasingly as well.

The restrictive behavior of the OPEC is unbroken and the capacities of the conveyors are just enough to meet the world's demands. The scarcity of energy fosters high efficiency, despite the worldwide application of sustainable and intelligent processing of raw materials and better recycling processes; the raw material market is recovering just slowly.

Environment: Efficient use of material and regenerative energy prevent energy crisis.

However, raw material bottlenecks can still be met largely through a slightly increasing expansion of regenerative energy sources. The resources of mineral and energetic raw materials are now estimated to meet the demand of the next 40 years. According to the recent developments, a broad consensus for environmental protection has been emerging worldwide. The population is convinced that a livable world should be preserved for future generations.

2.1.2 Future Aircraft Production

The future aircraft production is described by 13 key factors.

The future aircraft production was described on the basis of 13 key factors, encompassing statements on suppliers, market, branch technology and regulations [GEK+11]. In total, three scenarios for the future aircraft production were developed. The selected reference scenario characterizes a future where "Individual Customization Fosters Additive Manufacturing Technologies". Due to the successful part implementation, additively manufactured parts start to be associated with high performance and high quality. In the following section this scenario is briefly outlined and visualized in figure 2-2.

Suppliers: Intense cooperation between mega suppliers and aircraft manufacturers.

The cooperation between aircraft manufacturers and suppliers of the aircraft industry has been improved significantly through partnerships. More responsibility has been transferred from OEMs to suppliers: the suppliers contribute their own ideas to solve problems and develop all components under constant consultation with the manufacturers.

Simultaneously, the market accessibility for suppliers has changed considerably: as the size of orders has increased within the last years, only mega suppliers were able to handle these quantities – the number of orders handled by small suppliers decreased. The takeover of small suppliers became a more appropriate method to acquire new customer groups and expand market power.

Market: Number of aircraft variants has been increasing.

Due to branding as a continuing marketing trend, aircraft manufacturers have been increasing aircraft variety; each aircraft is progressively getting individual.

Branch technology: AM-parts are partly used for safety relevant parts; part properties have become tailor-made.

As parts produced by AM-processes started to be associated with high performance and high quality, many manufacturers jumped on board, and started to further invest into these technologies. For instance, additively manufactured parts are used for critical parts or for low scale production. Many new materials enter the market, enabling lower production costs and the implementation of new technologies due to excellent properties. Furthermore, new materials/machines allow the customization of material properties, as tailor-made part properties have become possible by now.

Branch technology: Functional-driven design is the key to success.

Due to intense research in AM, the ratio of functionality and costs has been improved and functional-driven design is the key to success. However, production-driven design is still prevalent in just a few limited cases in order to minimize production costs. Highly-automated processes largely substitute hand-crafted steps. In addition, energy-efficient aircraft can be realized due to new high-tech materials enabling higher working temperatures. The increased efficiency of engines reduces fuel consumption.

Regulations: Common set of certification standards has been developed.

Progressively, a common set of standards for AM has been elaborated. Due to the commitment of almost all aircraft manufacturers and many suppliers to implement AM-technologies in the production of aircraft parts, certification institutions have recognized the importance of the technologies; a common understanding in the value chain has been created. Furthermore, requirements on noise reduction of aircraft push AM-technologies.

Figure 2-2: Visualization of the reference scenario for the aircraft production "Individual Customization Fosters Additive Manufacturing Technologies" (pictures courtesy of: see picture credits on page 105)

Newly developed materials as well as innovative and industry-suited recycling methods now enable high recyclability. Partly, the shortage of raw materials and the increasing environmental responsibility have initiated the international community of states to determine worldwide regulations on aircraft recycling.

The selected reference scenario for the aerospace industry describes a world, where Europe sets the pace in a globalized world. The aircraft production is characterized by individual customization of aircraft, fostering the application of AM-technologies.

2.1.3 Future Automotive Production

The automotive production in 2020 is characterized by 13 key factors.

The future automotive production is described by 13 key factors, comprising statements on suppliers, market, branch technology, automotive concepts and regulations [GEK+11]. Based on future projections of these key factors, three scenarios for the automotive production were developed; the scenario **"New Production Concepts Drive Individuality"** was selected as reference scenario. The following section briefly describes this scenario; figure 2-3 visualizes the scenario. The automotive market has become highly competitive. Due to lower profit margins, the percentage costs for part shipping have risen. Suppliers and manufacturers were forced to intensify their cooperation. On the one hand, a factory in factory

Suppliers: Increased cooperation between suppliers and manufacturers due to competition

production is growing in order to save logistic costs. On the other hand, a worldwide localized production is still on demand to globally guarantee a fast supply of parts. Mega suppliers and small specialists work side by side. While 0.5 tiers as mega suppliers develop and produce whole vehicle modules, small specialists serve niche markets focusing on only a few business fields.

Figure 2-3: Visualization of the reference scenario for the automotive production "New Production Concepts Drive Individuality" (pictures courtesy of: see picture credits on page 105)

Market: Spare part business is of high importance; green production has prevailed.

Product life time of automotives has increased. As storing high amounts of spare parts is still very expensive, longer life times are realized by higher quality of automotive parts. Green production is highly important for sales today.

Branch technology: AM is used in series production for small lot sizes.

Automotive concepts: Individualized high-tech cars and conventional mass cars side-by-side

An intense material research has led to new high-tech materials with overwhelming qualities. The increased competition led to lower prices which has been resulting in a highly growing demand. Furthermore, series production of automotive parts is possible by now, and functional-driven design is the key to success. Parts designed for AM are only produced in small lots and small sizes; to minimize production costs, the most automotive parts are still designed production-technology-driven. Single parts are built just in time in order to keep up the existing schedule. The production processes are highly scalable; the assembly lines increasingly consist of highly flexible robotics. The role of the automobile in society is ambivalent. Although prestige and the need for individuality still play an important role for buying decisions, among some customer groups emotionality partly yields to pragmatism. Therefore, two different future car concepts are prevailing: individualized high-tech cars and conventional mass cars. Cars became more expensive than ever before, as core customization, that is due to highly individual customer requirements, raises the costs along the whole value chain. To counter this development, individualized production is being combined with modularized customization.

Regulations: Certification is possible, but still requires high effort.

Due to the commitment of almost all automotive manufacturers and many suppliers, certification institutions recognized the importance of the technologies for the automotive production; common requirements for the certification of AM-parts were widely defined; manufacturers adjust their new products in accordance with these requirements. Despite the increasing level of certification, still partly varying levels drive costs; certification of finished parts and processes (material powder, machine etc.) still requires high effort. The discussion on legislation on fuel consumption is calming down due to the availability of alternative power train concepts.

The selected reference scenario for the automotive industry describes a world, where Europe sets the pace in a globalized world. The future automotive production is characterized by new production concepts driving individuality of automotives.

2.1.4 Future Electronics Manufacturing Equipment

The future of the electronics' manufacturing equipment is outlined by 13 key factors.

For the electronics industry, the manufacturing equipment was selected as the focus to think ahead the future. Using 13 key factors, three scenarios for the electronics industry manufacturing equipment were developed, comprising statements on suppliers, market, branch technology and regulations [GEK+11]. The selected reference scenario characterizes a future where **"Highly Integrated Production Systems Allow Individualized Production"**. In the following, this scenario is briefly described and visualized in figure 2-4.

Suppliers: Value-added networking is on the rise.

In the outlined future of the electronics manufacturing equipment, networks between global and regional operating manufacturers have been evolving: manufacturers are strongly cross-linked, as value-added networking has been proven as an appropriate method to mutually increase competencies.

Market: Increasing customer influence fosters high variety of manufacturing equipment.

Increasing complexity of tool manufacturing projects fostered a closer networking with customers; customer influence is on the rise. Due to the growing demand for individually customized products, innovation is considered to be the key for success within the electronics industry. The resulting high innovation speed is progressively shortening product life cycles.

As customers are willing to pay higher prices for individuality, the number of orders that are accepted beneath the cost-recovery has been immensely reduced, compared to 2011; the price pressure on companies has been decreasing. Due to these developments, individual production systems have been prevailing. This causes a very high product variety for the suppliers of manufacturing systems. To counter this development, modularized customization of production systems realized by software has been prevailing.

Figure 2-4: Visualization of the reference scenario for the electronics manufacturing equipment "Highly Integrated Production Systems Allow Individualized Production" (pictures courtesy of: see picture credits on page 105)

Branch technology: device-free production lines are partly established.

Progressively, intelligent processes and process monitoring prevail. These reduce the need for intelligent devices, and device-free production lines have been partly established in the electronics industry. Due to increased research, improvements of AM-processes were realized. Standardized design rules, that are instrumental for part creation via AM, have been developed, and are continuously extended. Today, functional-driven design is the key to success, as the ratio of functionality and costs has been improved progressively.

The compatibility of AM-processes with conventional manufacturing processes is no challenge anymore; the entire integration is possible by now. Low standardization of electronic products pushes flexibility of production systems. Highly flexible production systems are being realized; life cycles of these production systems have extended.

Branch technology: Software dominates production processes.

Increasingly, manufacturers face the challenge of raising complexity. They succeeded to develop appropriate software solutions, and software takes over entire production processes; only boundary conditions are predefined. Intense material research provides new materials with overwhelming qualities and properties; these high-tech materials are widely used.

Regulations: Certification still requires high effort.

Suppliers and customers recognized the importance of AM-technologies. This forces certification institutions to define common requirements for certifying AM-parts. Thus, a common understanding in the value chain has been established. In some exceptional cases, certification institutes imposed requirements in terms of new certification barriers.

These varying levels of certification drive costs; certification of AM-parts and processes (material powder, machine etc.) still requires high effort.

The selected reference scenario for the future electronics manufacturing equipment describes a world, where Europe sets the pace in a globalized world. In this scenario, increasing customer influence fosters high variety of manufacturing equipment; highly integrated production systems for individualized production prevail.

2.1.5 Scenario-Transfer – Future Success Factors and Strategic Directions for Direct Manufacturing

The future scenarios expand the view for possible future developments. Through the scenario transfer, scenarios prove to be useful for strategic management decisions, as they constitute a profound basis for the development of strategies. In the scenario transfer the impact of the scenarios on the field of conception is analyzed. As a result, success potentials for the business of tomorrow and threats for the established business can be derived.

Deduction of success factors and strategic directions for the future AM-business

Using the scenarios, future success factors and resulting strategic directions for the application of AM in the selected industries were deduced. The following sections provides an excerpt of the future success factors and the strategic directions; for detailed information see the study “Thinking ahead the Future of Additive Manufacturing – Analysis of Promising Industries” [GEK+11].

Future Success Factors

- Certification is likely to turn into a future success factor for the AM-industry. Firstly, it is important to agree on **uniform certification** in order to strengthen trust in AM-parts. Secondly, certification processes need to be developed, facilitated and accelerated.
- **Qualification of personnel** will be an important success factor for the future AM-business. Engineers need to be qualified for designing functionally integrated parts and for the integration of AM-technologies into existing production processes.
- **AM-machines** have to be advanced for producing **larger parts** at a significantly higher speed. Especially, the aerospace and automotive industry will foster this development.
- **Customer integration** will be crucial to guarantee a fast and appropriate integration of customers/customer requirements into product development processes.
- **New materials** that can be processed with existing materials and AM-machines which enable an **On-the-Fly Change of Materials** within the production process need to be developed.

- AM-technologies have to be integrated into existing processes. Therefore, the **adaptability of AM-machines with conventional production lines** has to be increased to higher the flexibility of production processes.

Strategic Directions

Based on the analysis of the reference scenarios for the three industries, strategic directions have been developed by the experts.

Aerospace industry: Integration of the supply chain

The reference scenario for the future aircraft production describes a world, where Europe sets the pace in a globalized world. The aircraft production is characterized through individual customization of aircraft which fosters the application of AM-technologies. For being successful in the outlines future aircraft production, an integration of the supply chain will be crucial. This implies building up general ground rules for design of secondary aircraft structures and systems, and flowing them down to suppliers.

Automotive industry: Increasing productivity of AM-processes and quality of AM-parts

The future automotive production, also including the presented scenario for the global environment, is characterized by new production concepts that drive individuality of automotives. Increasing productivity of AM-machines and improved quality of additively manufactured parts will be required for a successful penetration of AM-technologies in the automotive industry.

Electronics industry: Enabling AM-process and materials for highly integrated production

The reference scenario for the future of the electronics manufacturing equipment shows a development in which highly integrated production systems enable individualized production. For being successful in this future, AM-processes and materials have to be qualified for highly integrated production.

2.2 Future Applications

Product discovering within the aerospace, automotive and electronics industry

This chapter covers the *Product Discovering*. The objective is to develop and specify ideas for new products and services in order to exploit the success potentials identified in the foresight process for the aerospace, automotive and electronics industry. Hence, the mentioned scenarios were used as an impulse to develop ideas for future applications of DM. 120 ideas were created across the three industries. These were clustered to 27 innovation fields.

2.2.1 Proceeding in the Project

For each industry, creativity workshops were conducted.

Against the background of the selected reference scenario combinations, (see chapter 2.1) creativity workshops with experts from the DMRC and external experts were conducted. The expertise of the experts involved in these workshops was wide-ranging from machine and material manufacturers to research facilities and users of AM-technologies from the aerospace, automotive and electronics industry. Through the visualization of the scenarios, the experts get an idea of how the areas of application for their products may look like in the future. Based on this, application ideas were developed and documented in idea characteristics. Similar ideas were clustered to innovation fields, containing concrete product ideas, or ideas for potential activities in the considered industry.

Subsequently, the identified product ideas/innovation fields from each industry were analyzed in detail to chances and risks resulting from market and technology perspective. A higher customer benefit provided through AM and a high market potential are chances, as these aspects enhance the attractiveness of an application. In contrast, high degree of competition and high investments into research and development represent risks for the realization of an idea.

Based on this data, the innovation fields were prioritized. The innovation fields identified to be the most promising for the application of DM in the future are concretized through realization and implementation studies within specific workshops and through market research. Furthermore, the innovation fields were examined in detail to deduce requirements the applications impose on developments of AM-technologies towards DM.

2.2.2 Future Applications – Aerospace Industry

In this chapter, the innovation fields for the aerospace industry are presented [Wor11a]. In total, 37 product ideas were developed. These were clustered to 9 innovation fields that are briefly outlined in the following. A more detailed description of the innovation fields/ applications is provided in the previous study “Thinking ahead the Future of Additive Manufacturing – Future Applications“ [GEK+12]. All applications are described in the confidential study.

37 application ideas for the aerospace industry were developed and clustered to 9 innovation fields.

Idea Creation and Documentation

- **Aircraft Interior** comprises AM-parts with innovative design that concurrently contribute to reduce the total weight of an aircraft and to improve passenger comfort and safety as well as ergonomics in the aircraft. For instance, interior parts with lattice structures could be used to combine high strength with a relatively low mass. Individual or reconfigurable interior becomes possible as well, e.g. individually configured, functionally integrated aircraft seats, including self-adjusting mechanisms for automatic adaption to movements.

- **Multifunctional Structures** include ideas for functionally upgraded parts. Upgraded functionality can, for instance, be realized by integrating acoustic and thermal insulation into aircraft parts or by embedding entire sensor/actuator systems, including electronic wiring and connectors into a part. This can contribute to realize self-optimizing parts [Bar11], [Wor11b].

- **Energy Saving/Providing Structures** bear further opportunities to intelligently apply AM-technologies. These structures are capable to store kinetic energy and release it when needed. This also comprises parts connecting areas of different temperatures in an aircraft which could be used as thermoelectric generators [Zul11-ol].

- **Monolithic Structures** are parts that are made from one part with comparatively simple geometry. So far, frames, wings, flaps, ailerons etc. are assembled from different small parts which require a lot of machining and custom tooling. Printing monolithic parts can contribute to increase part stability to reduce production and assembly costs.
- **Morphing Structures** describe applications which are designed as one part capable to adapt in its shape in response to the operational environment. Instead of changing the position of a static part by using actuators, the part itself can take continuous configurations of its shape to enable specific functions/properties.
- **Deployable Structures** follows the example of the medical industry that uses the idea of structural “blow up” for expandable stents to broaden coronary vessels. The main idea is to produce parts in small sizes and to expand them to the required size in a subsequent step, e.g. by heat treatment or telescoping expansion [AFR10], [MRB+07], [Wor11a].
- **Smart Joinings** follow the idea to enhance the design of parts for improved connectivity. The main purpose is to replace connectors, such as bolts and screws, which weaken the structural integrity and also represent a considerable cost factor.
- **Out-of-Chamber Manufacturing** is an idea that emerges from the demand for manufacturing large parts with AM-technologies. The vision is a completely innovative manufacturing mechanism, combining single AM-machines/AM-robots to an integrated Out-of-Chamber Manufacturing system in a scalable way.
- **Manufacturing on Demand** refers to the flexibility of AM-technologies to produce parts just-in-time. Thereby, storage costs can be reduced significantly, and furthermore on-demand-production fosters the intactness of parts because no damaging can occur during storing. This idea is especially interesting for on-site manufacturing.

In the following, exemplary application ideas from two selected innovation fields are described in detail. The characteristics encompass a short description, a draft, the current technical solution, advantages and disadvantages of applying AM.

Figure 2-5 characterizes an application for *Multifunctional Structures*. One example for *Morphing Structures* is outlined in Figure 2-6.

Idea Selection

Innovation fields were assessed regarding chances and risks.

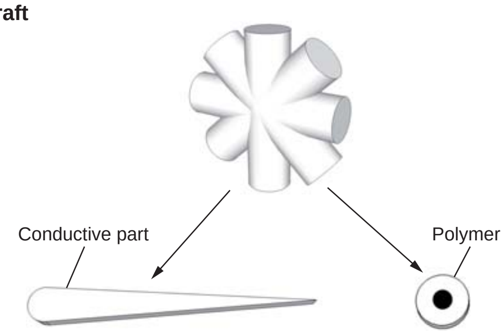
The identified innovation fields considerably differ in their attractiveness for the application of AM-technologies. Some application ideas can be realized with a relatively low effort; other ideas require extraordinary charges. Similarly, the market potential of a product idea can differ. To select the most promising innovation fields/product ideas, the experts have prioritized the innovation fields by rating the chances and risks resulting from market and technology perspective.

Embedded Sensors

Description

AM-technologies enable multiple design features, such as embedding sensors inside a functional part like aircraft fuselage and wings. Thereby, smart and highly functional products of any shape can be provided [Li01]. By integrating embedded sensors into aircraft structures, data on the performance and structural integrity of the part can be obtained and physical parameters could be continuously monitored. In order to receive high quality data, for instance precise data for lifetime estimations, sensors have to be placed in structural parts of aircraft which are difficult or hardly accessible by regular sensing systems. This allows the optimization of service intervals, which on the one hand raises the reliability of parts and on the other hand lowers costs, as parts are only replaced when needed. The basic prerequisite for such embedded intelligence is the incorporation of sensors into structures during the production process of the part [Wor11a].

Draft



Advantages/Benefits

- Higher efficiency of service and repair
- Functional literate
- More responsive
- Stealth manufacture
- Increased reliability of parts

Disadvantages/Risks

- High reparation costs
- Implication of failure not assessible
- Probably cooling problems
- Increased part complexity

Current Technical Solution

Using conventional manufacturing technologies, sensors are placed in non-optimal positions. If urgently needed, sensors are additionally installed, which is cost-intensive.

Type of Idea

☐ product update ☐ adaption ☒ innovation

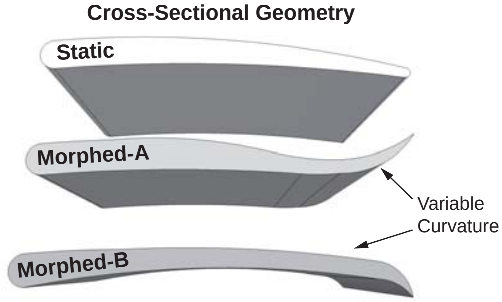
Figure 2-5: Exemplary idea from the innovation field Multifunctional Structures: Embedded Sensors

Morphing Wings

Description

The ability of AM to produce highly flexible and functionally integrated parts fosters the idea to create "smart" parts that quickly adapt/react in response to the operational environment – the so called Morphing Structures. For instance, by varying the cross-sectional shape, a morphing wing, providing the laminar flow of the air over the aerodynamics and control surfaces, could adapt to respective flight phases and high-speed phenomena [Wei06-ol]. Thereby, the buoyancy can be varied and viscous drag can immensely be reduced [Nat11-ol], [HKF10]. This effect can be realized more efficiently and with less turbulence by the modulation of the wing geometry. Moreover, these wings enable better aerodynamics compared to conventional wings, as affections by wind gusts can be compensated quickly by adjusting the airfoil and its stiffness [Wor11a].

Draft



Advantages/Benefits

- Fewer moving parts
- Less wiring needed
- Weight reduction
- Better aerodynamics
- Economic flying during the flight is possible (reduced fuel consumption can be exploited otherwise)

Disadvantages/Risks

- Durability of materials
- High material and repair costs
- Emergency flight properties during a system crash

Current Technical Solution

Movable control surfaces (horizontal tail and flaps) are used to change air flow/wing configuration.

Type of Idea

☐ product update ☐ adaption ☒ innovation

Figure 2-6: Exemplary idea from the innovation field Morphing Structures: Morphing Wings

Based on this, each innovation field can be positioned in a chances-risks-portfolio, as shown in figure 2-7. For the innovation fields, the ordinate intercept shows the chances; the abscissa intercept indicates the risks.

Most promising innovation fields in the aerospace industry: Morphing Structures and Multi-functional Structures

The closer an innovation field is to the top left corner, the higher the attractiveness of the innovation field for the application of DM. The innovation fields *Morphing Structures* and *Multifunctional Structures* were highly prioritized, as they offer the greatest potential for the application of DM. These were concretized in more detailed characteristics. The concretization specifies the opportunities and barriers that arise from the application of AM-technologies, and assesses the technical feasibility. For more information see [GEK+12] and confidential study.

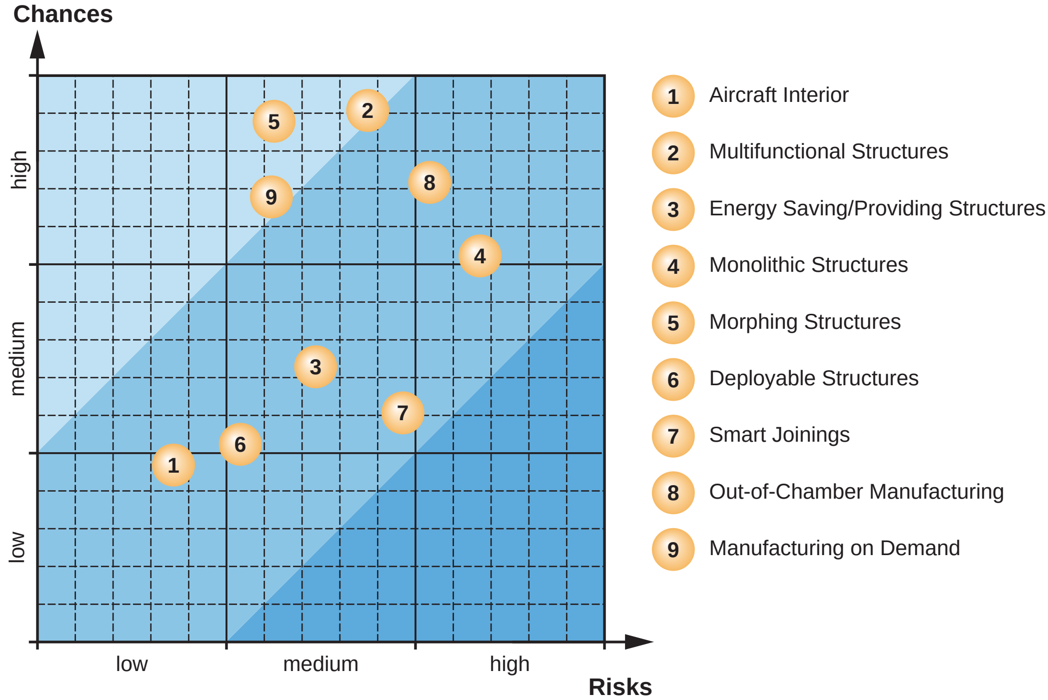


Figure 2-7: Prioritizing innovation fields of the aerospace industry using a chances-risks-portfolio

Innovations for AM arise around a broad variety of aircraft parts. Most importantly, additively manufactured parts can contribute to significantly increase efficiency of aircraft. Additionally, passenger convenience and just-in-time spare parts can be improved and provided, respectively.

2.2.3 Future Applications – Automotive Industry

33 ideas for the application of AM in the automotive industry, were developed and clustered to 8 innovation fields.

Using the reference future scenario as an impulse, 33 product ideas have been developed for the application of AM for the automotive production [Wor11b]. These ideas were clustered to 8 innovation fields that are briefly described in the following. For the most promising innovation fields exemplary application ideas are presented. A more detailed description of the innovation fields/applications is provided in the previous study “Thinking ahead the Future of Additive Manufacturing – Future Applications“ [GEK+12]. All applications are described in the confidential study.

Idea Creation and Documentation

- **Functional Body-in-White** comprises a wide range of functionally integrated AM-parts, reaching from channels/fluid conduits integrated into the body panel to customizable (tuning, structural color etc.), and safety-increased structural parts. These parts can contribute to improve body stiffness and stability of parts [Red11-ol].

- **Individualized Interior** arises from the idea to flexibly meet special customer demands with regard to highly customized car interior as a unique selling point. The principle “Freedom of Design” enables the creation of improved handling configurations for switches, pedals, entire dashboards or seats which are configurable to meet the individual specifications on comfort, passive safety etc.

- **Optimized Tooling** includes ideas for the integration of channels into tooling parts to improve the durability and resistance of tools. By applying AM-technologies in this sector, a more flexible way of arranging cooling channels can be achieved; cross-sections of cooling channels can take any arbitrary shape. Thereby, uniform heat dissipation and quicker cooling processes can be realized [May09-ol], [NDS+04-ol], [Wor11b].

- **Handling of Fluids** describes parts that focus on geometric adaption of pipes, valves, restrictors etc. to individual purposes. Depending on their application, these parts have to be improved, for example with regard to optimized exchange of thermal energy and gas distribution, critical strength properties, and weight or reduction [TCT10-ol], [Wor11b].

- **Parts on Demand** comprise ideas that emerge from the desire to reduce the extraordinarily huge scale of storing spare parts in the automotive industry. Improvements in this sector bear an immense opportunity to save costs, especially as tooling for special spare parts is even more expensive.

- **Optimized Power Train** is an idea that is motivated by the trend of increasing, environmental awareness in society. This demands for alternative optimized or completely new power train concepts, e.g. fuel cell, gas etc. AM opens up possibilities for weight/size reduction of power train parts, the integration of functions into structures, directly where needed.

- **Electric Drive** comprises ideas for applications that exhaust the “Freedom of Design” provided by AM to generate new aggregates, featuring advanced functionality. With electric cars being on the raise, it seems to be more suitable to implement new manufacturing technologies at this early stage of development than to intervene in established production processes.

- **Functional Material/Multi-Material** includes ideas of two categories: totally new functional materials (Au8.1) and existing material with incrementally improved functionality (Au8.2). The core purpose of applying such materials in a part is to enable additional properties, e.g. electrical or thermal conductivity, self-healing properties – or the combination of tough metals with heat-resistant ceramics.

In the following, exemplary application ideas from two selected innovation fields are described, comprising a short description, a draft, the current technical solution, advantages and disadvantages AM provides. Figure 2-8 characterizes tools with integrated channels from the innovation field *Optimized Tooling*. One example for *Handling of Fluids* is outlined in figure 2-9.

Idea Selection

Innovation fields were ranked regarding chances and risks.

There are great differences between the innovation fields regarding their attractiveness for the application of AM-technologies. They differ concerning the market potential or with regard to the required development effort. In general, the most promising innovation fields/application ideas should be pursued. To prioritize the innovation fields, the experts rated the chances and risks resulting from market and technology perspective.

Based on the assessment, each innovation field was positioned in a chances-risks-portfolio, as shown in figure 2-10. For the innovation fields, the ordinate intercept shows the chances; the abscissa intercept indicates the risks.

Handling of Fluids and Optimized Tooling were highly prioritized.

The closer an innovation field is to the top left corner, the higher the attractiveness of applying AM in this innovation field. The innovation fields *Handling of Fluids* and *Optimized Tooling* were classified as the most promising. These were concretized in more detailed characteristics, addressing opportunities and barriers of DM, the technical feasibility and the advantages in comparison to the application of conventional technologies.

Tooling with Integrated Channels

Description

Due to AM's ability to economically manufacture geometrically complex structures, tooling with optimized cooling/heating channels, which are directly integrated into a tooling insert, can be created in one piece. Cross sections of the channels can take any shape and be individually adapted to the contour of the part cavity. Thereby, component-specific conformal cooling/heating is possible, as the channels are close to the stressed surfaces [May09-ol]. This is more efficient and directly reduces solidification time and cycle times [NDS+04]. In addition, materials with special properties such as high thermal conductivity can be applied. All in all, owing to tools with integrated channels, part performance/quality can be improved [Wor11b].

Draft

Advantages/Benefits

- Fast production of geometrically complex tools
- Stiff materials are already available
- Higher productivity
- Higher part quality due to more durable tools
- Lower energy consumption per product unit
- Cooling capacity is superior due to compact size and complex geometries [NMG+11-ol] [May09-ol]

Disadvantages/Risks

- Manufacturers need to be qualified with AM-design methods
- More complex geometry could lead to higher engineering costs

Current Technical Solution

Currently, tools for automotive parts are manufactured with straight integrated cooling channels. In general, cooling close to the stressed surface is difficult. However, there are approaches focusing modular design of the components. For instance, using DMLS, EOS already manufactures tools with conformal cooling channels that are used to produce millions of parts in injection moulding operations or many thousand metal parts in die casting [May09-ol].

Type of Idea

☐ product update ☐ adaption ☒ innovation

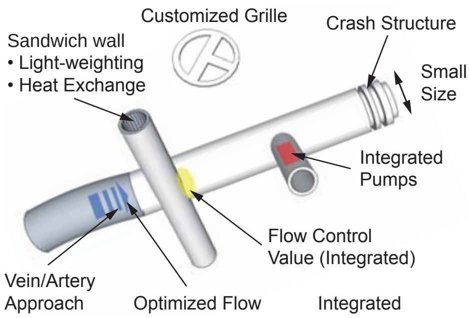
Figure 2-8: Exemplary idea from the innovation field Optimized Tooling: Tooling with Integrated Channels

HVAC (Air-Conditioning)

Description

The usage of AM-technologies in the production field of heating ventilating and air conditioning (HVAC) allows the production of a superior product generation. AM allows the realization of sandwich walls, reducing the weight of the part and decreasing the heat exchange in areas where it is not needed [Sch11-ol]. Furthermore, the functional integration of pumps, flow control valves or mounts reduces the amount of single components, which in turn leads to space savings and reduced part size. In addition, the time for assembly can be minimized. It might also be possible to integrate crash structures to realize a better passenger protection. Moreover, the part design/shape can easily be adapted to perfectly fit into different cars [Wor11b].

Draft



Advantages/Benefits

- Reduction in volume/weight
- Mass customization
- Highly efficient product design
- Reduction in consumption
- Reduction in parts and assembly costs
- Higher durability

Disadvantages/Risks

- Multi-material/functional material problems
- High reparation costs
- High part complexity

Current Technical Solution

Today, rectangular cooling rips and heat exchangers with only a few liquid channels are applied.

Type of Idea

☐ product update ☐ adaption ☒ innovation

Figure 2-9: Exemplary idea from the innovation field Handling of Fluids: HVAC (Air-Conditioning)

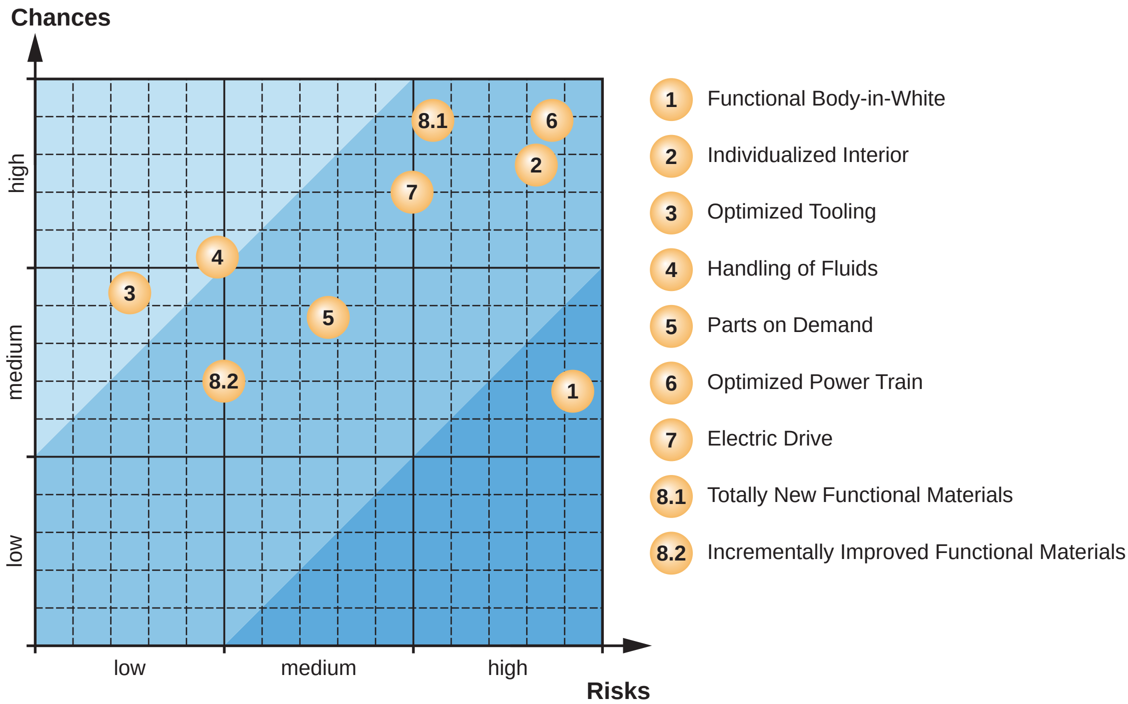


Figure 2-10: Prioritizing innovation fields of the automotive industry using a chances-risks-portfolio

AM offers a wide range of DM-applications in the automotive industry. Besides functional innovations, the need for new alternative power train concepts opens up innovation fields such as electric drives. Furthermore, AM can excel at designing and manufacturing of tools.

2.2.4 Future Applications – Electronics Industry

28 application ideas for the electronics industry were developed and clustered to 8 innovation fields.

This chapter provides a brief overview of the innovation fields for the electronics industry. In total, 28 application ideas were developed; these were clustered to 8 innovation fields [Wor11c]. The previous study "Thinking ahead the Future of Additive Manufacturing – Future Applications" provides a more detailed overview on innovation fields/applications [GEK+12]. All applications are part of the confidential study.

Idea Creation and Documentation

- **Additive Factory** combines ideas which promote flexibility by using AM for direct and integrated manufacturing of electronic components. The spectrum of ideas in this field ranges from the entire replacement of conventional manufacturing technologies by multi-energy, multi-tool and multi-laser AM-machines – the so called Multi-Replicators – to "free-space" layer-wise manufacturing machines.
- **Adaptive Components** cover a wide range of adaptive AM-parts. This comprises adaptive electronics with different shapes and different orientation, the integration of electronics into

hardly accessible positions, and 3D-structures with locally altering material properties, such as required conductivity, stiffness, strength properties etc.

- **Testing Systems** give rise to a set of ideas around electric control cabinets or circuit board assemblies. Additively manufactured testing equipment can be produced including all required, individually arranged attachment points. Thereby tests of electric control cabinites could be carried out in a single step.
- **Fuel Cells** comprise ideas for geometrically complex parts, consisting of a multitude of different materials. Due to the layerwise principle of AM, different materials could be combined on layer level, concurrently enabling smoother transitions, higher mechanical stability, power density and efficiency, and better suited material properties. As opposed to common fuel cells, energy-efficient designs and better material utilization rates could be realized [Opt10-ol].
- **Material Combinatorics** is an idea that emerges from the demand for higher functionality of electronics. AM-technologies may revolutionize the multi-material design, as different materials could be combined on layer-level. This for example allows integrating strings of conductive materials in a non-conductive material environment.
- **Functionally Integrated Parts** encompass application ideas which focus on embedding electronics (circuits) into all kind of geometries and on functional integration of different electronic devices into a single part, following the principle of the Molded Interconnect Devices (MID)-technology [Wor11c].
- **Tooling** and manufacturing equipment used in the production of electronic parts is required in shorter intervals, due to the rapid technological advance in the electronics industry. AM-technologies offer the required flexibility to produce tools or inserts for tools in one manufacturing step. Moreover, AM can function as a tooling substitute by manufacturing electronics parts directly with AM-machines.
- **Handling Systems** includes ideas for optimized pick and place systems. Due to AM's flexible use of different materials and e.g. the principle of lattice structures, grippers and other devices can be produced with a light-weight interior and a hardened frame. These could also be equipped with integrated testing functions and adaptive construction mechanisms that enable gripping different components.

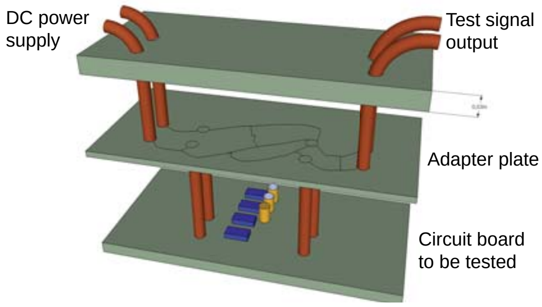
The following section outlines exemplary applications from two selected innovation fields, providing a short description, a draft, the current technical solution, advantages and disadvantages. Figure 2-11 describes a special holder for test adaptors from the innovation field *Testing Systems*. Individual boxing is an exemplary idea for *Functionally Integrated Parts* and is outlined in figure 2-12.

Special Holder for Test Adaptor

Description

The high flexibility of AM in designing parts is making this manufacturing technology suitable for the creation of geometrically complex holders for special test adaptors that are often needed in the electronics industry. Especially, test equipment for quality control is often produced in small lot sizes, as it is adjusted to highly individual purposes. Holders can be adapted to be perfectly dimensioned for every single experiment without increasing production costs [Rij11]. The holding fixture for testing points can be individualized as well, making the execution of tests more exact [Wor11c].

Draft



Advantages/Benefits

- Light-weight structure
- Short production times
- Low cost production

Disadvantages/Risks

- Keeping tolerances

Current Technical Solution

Today, test adapters are only adapted when urgently needed. A standard test adapter is often used for a series of different tests without being adapted in order to save costs [Wor11c].

Type of Idea

☐ product update ☐ adaption ☒ innovation

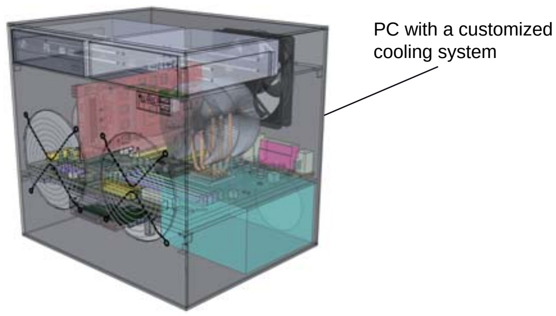
Figure 2-11: Exemplary idea from the innovation field Testing Systems: Special Holder for Test Adaptor

Individual Boxing

Description

High volume production of electronic devices often uses one and the same box for each variant of the product. This leads to suboptimal conductance or loss of energy (heat conductance). Furthermore, unused space in the boxing makes the device bigger than it needs to be, also raising packaging costs. By using AM-technologies, the design of the box can be adapted to every variant of the product without any changes of the production process. After being developed on the computer (potentially by using 3D scan systems), it can be printed instantly without the need of adapting tools and any additional machine set-up time. Beyond this, smart software systems could also allow automatically creating a boxing based on the CAD file of the product to be packed [Wor11c].

Draft



Advantages/Benefits

- Better conductance of heat
- Less unused space in the boxing
- Lower material consumption
- Better design possible

Disadvantages/Risks

- Subsequent changes might be critical
- Higher Costs

Current Technical Solution

Standardized boxing.

Type of Ideas

☒ product update ☐ adaption ☐ innovation

Figure 2-12: Exemplary idea from the innovation field Functionally Integrated Parts: Individual Boxing

Idea Selection

Innovation fields were assessed regarding chances and risks.

There are great differences between the innovation fields regarding their attractiveness for the application of AM-technologies. They differ concerning the market potential or with regard to the required development effort. Therefore, just the most promising innovation fields/product ideas have to be pursued. To prioritize the innovation fields, we asked the experts to assess the innovation fields regarding market and technology-related chances and risks. Based on these, each innovation field was positioned in a chances-risks-portfolio, as shown in figure 2-13. For the innovation fields, the ordinate intercept shows the chances; the abscissa intercept indicates the risks.

Most promising innovation fields for the electronics industry: Functionally Integrated Parts and Testing Systems

The closer an innovation field is to the top left corner, the higher the attractiveness of the innovation field for the application of AM. According to the experts' assessment, the innovation fields *Functionally Integrated Parts* and *Testing Systems* are the most promising, due to relatively high chances and low risks. These were concretized in more detailed characteristics. The concretization specifies the opportunities and barriers for the application of AM and proves the technical feasibility and the advantages in comparison to conventional technologies. For more information see [GEK+12].

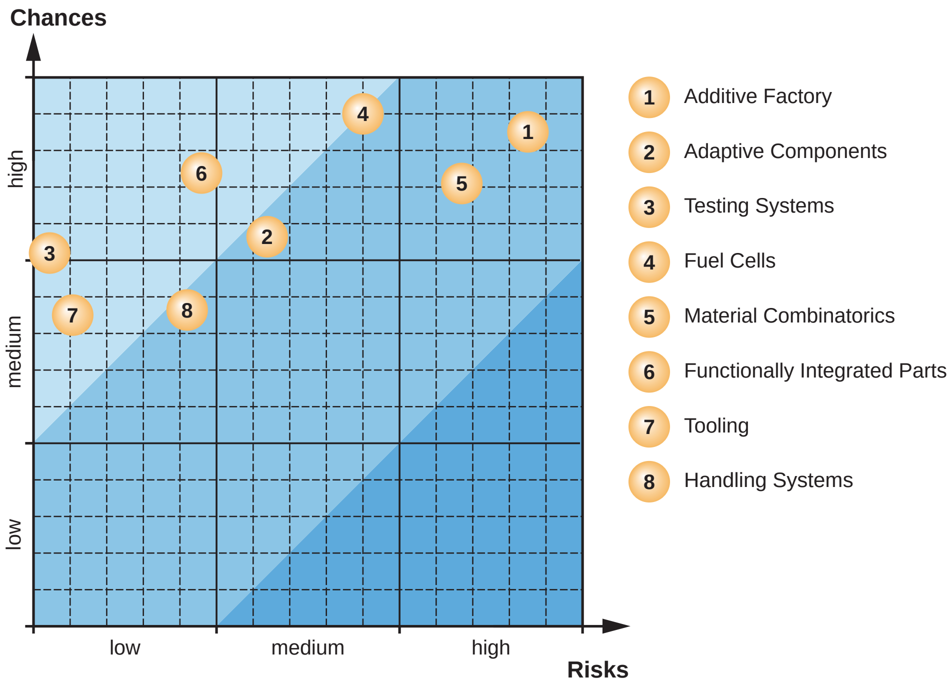


Figure 2-13: Prioritizing innovation fields of the electronics industry using a chances-risks-portfolio

AM provides great potentials for innovations in the electronics industry. Given the close interlacement with other industries, e.g. ideas for additively manufactured fuel cells emerge. Besides, testing or handling systems for the production of electronics give rise to promising ideas.

2.3 Deduction of Future Requirements

Technologies are the key drivers for innovations and thus decisive for the competitiveness of companies. Especially emerging technologies entail great potentials for disruptive innovations (Technology Push). To transfer their potential into innovations, it is necessary to align the technology development with current and future market requirements (Market Pull). This enables the AM-industry to develop and pursue demand-oriented technology strategies, and thus to effectively advance AM-technology into a dependable DM-technology.

Requirements on technological advancements were deduced from the innovation fields.

Following this idea, the developed innovation fields were analyzed in detail to deduce requirements on DM. The requirements constitute a profound basis for the deduction of required technological advancements of AM-technologies. The following section provides an excerpt of the deduced requirements. A comprehensive assignment of requirements to innovation fields is part of the confidential study.

As many of the identified requirements are decisive for more than one innovation field, the figure 2-14 shows an extract of the assignment, indicating which requirements (row) the innovation fields (column) impose on DM.

- **High process stability and certification of AM-processes and AM-parts** are relevant for the vast majority of the innovation fields across all three industries, especially for safety-critical parts.
- The **provision of generally accepted design rules** is a basic prerequisite for the most innovation fields in order to minimize costs and time effort for design.
- **On-line quality control** processes are for instance crucial for the innovation fields *Aircraft Interior* and *Functional Body-in-White*.
- The **processability of different materials** with AM-machines is a requirement that is relevant for e.g. the *Aircraft Interior* and *Morphing Structures*, as the materials used range from magnesium to carbon-fiber-reinforced polymers and other multi-material designs, respectively.
- To exploit the benefits of *Out-of-Chamber Manufacturing*, flexible AM-machines are required which are able to **build up on existing 3-D surface structures**, otherwise the simultaneous machining of more than one robot on one part is not possible.
- The availability of a **database containing properties of AM-materials** (e.g. thermal characteristics, tensile strength etc.) is very important for *Multifunctional Structures* and *Functional Body-in-White* in order to assess functional properties under all circumstances.

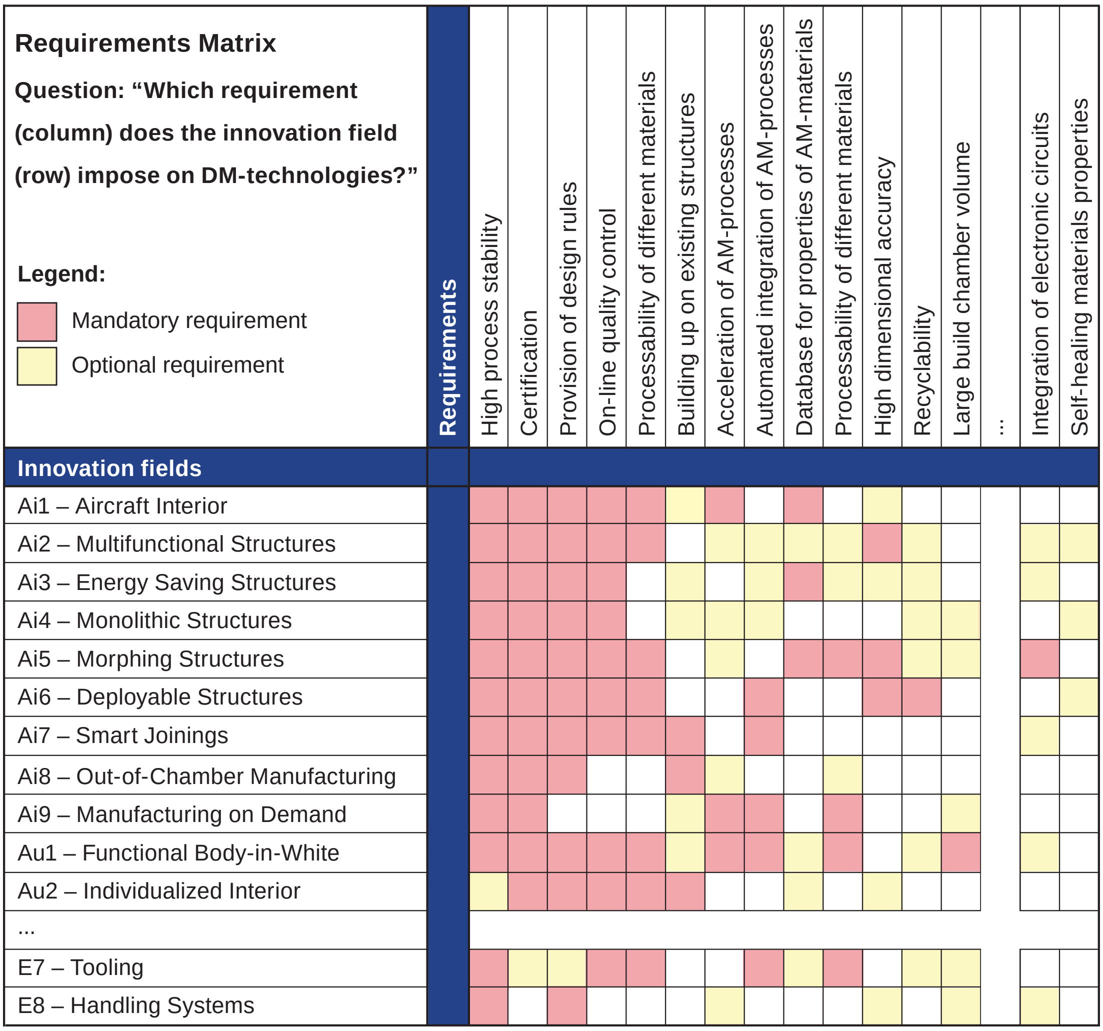


Figure 2-14: Deduction of requirements from innovation fields

> ***The application of AM in the identified innovation fields gives rise to a broad variety of requirements. For instance, process stability, certification, design rules, the ability to control the part quality during the production process etc. will play a key role for the penetration of AM in the future.***

2.4 Summary

To think ahead the future of AM in the aerospace, automotive and electronics industry, future scenarios were developed using the Scenario-Technique. The scenarios address the future aircraft and automotive production, and the electronics manufacturing equipment.

Future scenarios

The selected future scenario for the aerospace industry describes a world, where Europe sets the pace in a globalized world. The aircraft production is characterized by individual customization of aircraft which fosters the penetration of AM-technologies.

The selected reference scenario for the automotive industry, also including the presented scenario for the global environment, is characterized by new production concepts that drive individuality of automotives.

The scenario combination for the electronics manufacturing equipment also implies the previously selected scenario for the global environment. The electronics manufacturing equipment is characterized by highly integrated production systems enabling individualized production.

Future success factors

Based on the developed scenarios, future success factors were deduced. The most relevant factors are:

- Uniform certification,
- Qualification of personnel,
- AM-machines with larger build chamber volumes,
- Customer integration,
- New materials and on-the-fly change of materials in production processes,
- Adaptability of AM-machines with conventional production lines.

Strategic directions

On the basis of the success factors, strategic direction for being successful in the scenarios were developed. Building up general ground rules for the design of secondary aircraft structures, and flow them down to suppliers will be decisive to succeed in the future aircraft production. For a successful implementation in the automotive production, it is necessary to increase the productivity of AM-technologies and the quality of AM-parts. Success in the future of the electronics industry requires AM-processes and materials that are qualified for highly integrated production.

120 application ideas in 27 innovation fields were developed.

The selected reference scenarios for the aerospace, automotive and electronics industry with the greatest impact on the future of AM were used as impulse to develop ideas for future applications. The spectrum of the identified applications encompasses 120 ideas. These were clustered to 27 innovation fields, and prioritized based on the assessment of chances and risks.

The innovation fields identified to be the most promising for DM in future were concretized in specific expert workshops and through market research. For the aerospace industry, the experts rated the following innovation fields to be the promising for DM:

- **Morphing Structures** encompass ideas for the creation of parts that adapt and/or react in response to the operational environment. For instance, the cross-sectional geometry or the surface curvature of a wing could adapt to the respective flight/speed phenomena. Thereby, the flight performance and fuel consumption could be significantly improved and reduced, respectively.
- **Multifunctional Structures** are functionally upgraded parts. Upgraded functionality can be realized by integrating acoustic and thermal insulation into aircraft parts. Embedding entire

sensor/actuator systems, including electronic wiring and connectors can even contribute to realize adaptive or self-optimizing parts.

In the automotive industry, the innovation fields with the greatest potential for the application of DM are:

- **Handling of Fluids** focuses on geometrical adaption of pipes, valves, restrictors etc. to individual purposes. This can excel at optimizing the exchange of thermal energy and gas distribution.
- **Optimized Tooling** comprises ideas for integrating channels into tooling parts to improve the durability and resistance of tools. Cross-sections of cooling channels can take any shape to achieve uniform heat dissipation and quicker cooling processes.

For applying AM in the electronics industry, the following innovation fields were selected as the most promising:

- **Functionally Integrated Parts** comprise embedding electronics (circuits) into all kind of geometries and functional integration of different electronic devices into one single part, following the principle of the MID-technology.
- **Testing Systems** give rise to ideas around electric switch cabinets or circuit board assemblies. Additively manufactured testing equipment can be produced including all required attachment points enabling tests to be carried out in a single step.

Deduction of requirements

Based on the analysis of the innovation fields, requirements on necessary advancements of AM-technologies were deduced. This comprises requirements on process and material characteristics, such as hybrid material processing and the availability of new material properties, e.g. thermal conductivity and self-healing properties. Mandatory requirements across the most innovation fields are:

- High process stability,
- Certification,
- Provision of design rules,
- On-line quality control processes,
- Processability of different materials,
- Automated integration of AM-processes.

3

Strategic Technology Planning

To advance AM-technologies to DM, it is necessary to align the technology development with current and future requirements each application imposes on DM. This enables the AM-industry to develop and pursue demand-oriented technology strategies. To identify the most important requirements, the Heinz Nixdorf Institute and the DMRC conducted two expert surveys.

Two expert surveys on requirements and technological advancements were conducted.

As part of the first survey, the current and future significance of these requirements, and the performance of selected technologies regarding these requirements were validated. An excerpt of these results is presented in chapter 3.1. The second survey focused the advancements of AM towards DM. The main purpose was to get a sound overview of the point in time when – from AM-experts' point of view – the selected requirements will be fulfilled by selected AM-technologies. These findings were consolidated in innovation roadmaps, indicating when the identified future applications can be manufactured as technological requirements will be fulfilled. Excerpts of these results are outlined in chapter 3.2.

3.1 Future Requirements on Technological Advancements

This chapter presents the results of the expert survey on *Current and Future Requirements on DM-technologies* that was conducted to reveal the most important requirements. The expert survey is available in the appendix A1.

Structure and Proceeding in Expert Survey 1

Wide ranging expertise of participants

The survey was conducted in German and English in the period from October, 27th until December, 11th. To reflect the opinion of the entire AM-industry, the survey addresses AM-experts along the whole value chain: AM-machine manufacturers and material suppliers, users of AM-technologies (OEMs and suppliers) as well as universities and research facilities dealing with AM-technologies. The survey was sent to **325 AM-experts**; **56 contacts (17%)** completed the survey.

The survey is divided into four parts: *General Information, General Requirements, Technology-Specific Requirements and Final Statements*. The first part addresses the professional background of the experts. In the second part, the experts were asked to assess 7 general requirements regarding their significance and the performance of selected companies concerning these requirements. These results are not part of the present study. The third part comprises the assessment of technology-specific requirements regarding their significance and the technologies' performance concerning these requirements.

The final part outlines final statements of the experts. This chapter provides an excerpt of the results; more information is available in the previous study [GEK+12]; detailed results are part of the confidential study.

3.1.1 General Information

The majority of the participants are technology experts.

This chapter presents the professional background of the experts. First, the experts were asked to indicate their field of activity. 91% of all participants indicate to have expertise in the field of technology and 32% in market and competition. Secondly, the experts specified the part of the value chain of AM and the company division they are working in. The percentage distributions are shown in the following two bar charts (note: multiple choices possible). With a share of 41%, users of AM and research facilities count each the largest share among all participants, followed by consulting, material suppliers and machine manufacturers, see figure 3-1. The *Other* category includes participants that do not fit into the listed categories.

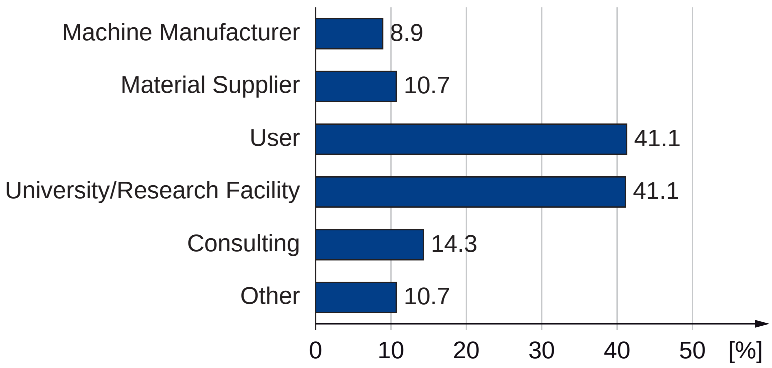


Figure 3-1: Part of the value chain the participants are working in (in percentage terms)

Figure 3-2 illustrates the heterogeneous composition of the participants, as the range covers all company divisions.

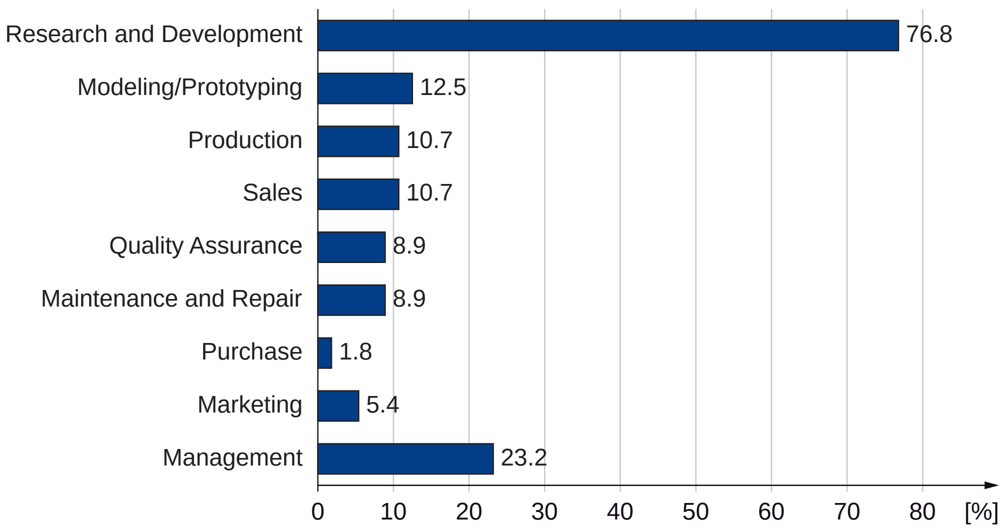


Figure 3-2: Company divisions the participants are working in (in percentage terms)

The majority of the participants (77%) specify to work in research and development. With 23%, the management division also comprises a large proportion.

The two bar charts in figure 3-3 illustrate in percentage terms how the participants uses AM, explicitly pointing out how the users of AM apply AM-technologies (note: multiple choices possible). At a first glance, the **specifications of the population and users of AM** correlate. Approximately, 70% and 78% of the participants and users, respectively, indicate to use AM for Direct Manufacturing. The usage of AM for Rapid Prototyping and Rapid Tooling is indicated to be more common for users. This also correlates with the fact that the majority of the participants indicates to work in research and development divisions (see figure 3-2).

Direct Manufacturing is indicated as a major application field for AM.

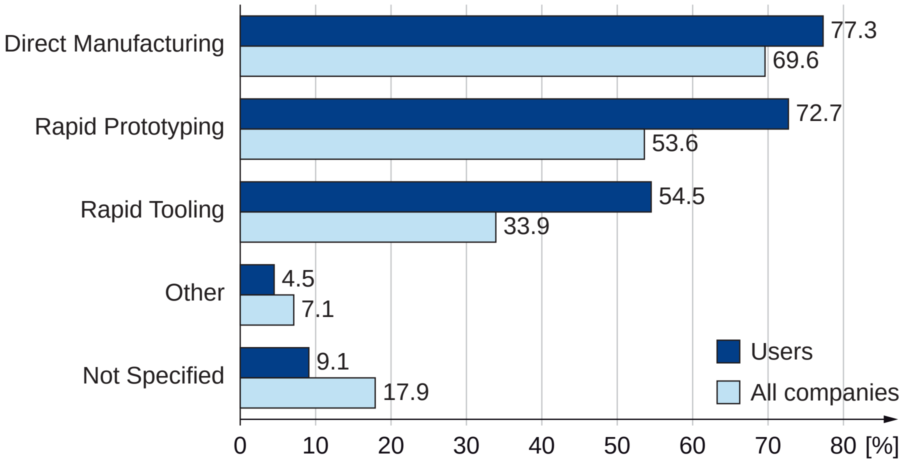


Figure 3-3: Usage of AM-technologies (in percentage terms), ***differentiating the users of AM (dark blue) and all participants (pale blue)***

3.1.2 Evaluation of Current and Future Significance of Requirements

This chapter outlines the experts' assessment of the current and future significance of technology-specific requirements. These requirements are directly technology-related, and have been derived from the innovation fields developed within the project (see chapter 2.2). The experts were asked to specify the significance of each requirement for the DM-industry from today's point of view and its significance in 2020, using a scale from "0" to "4" (no significance up to high significance). The goal of this assessment is the identification of those requirements which will be crucial for the business of tomorrow. Based on the assessment in the survey, the arithmetic mean was determined for both, the (current and future) significance of the requirements. In figure 3-4, the current (blue color) and the future significance (green color) for all technology-specific requirements is visualized.

Technology-specific requirements were deduced from the developed innovation fields.

Process stability, a database for AM-materials, on-line quality control processes, certification and design rules are and will be highly significant.

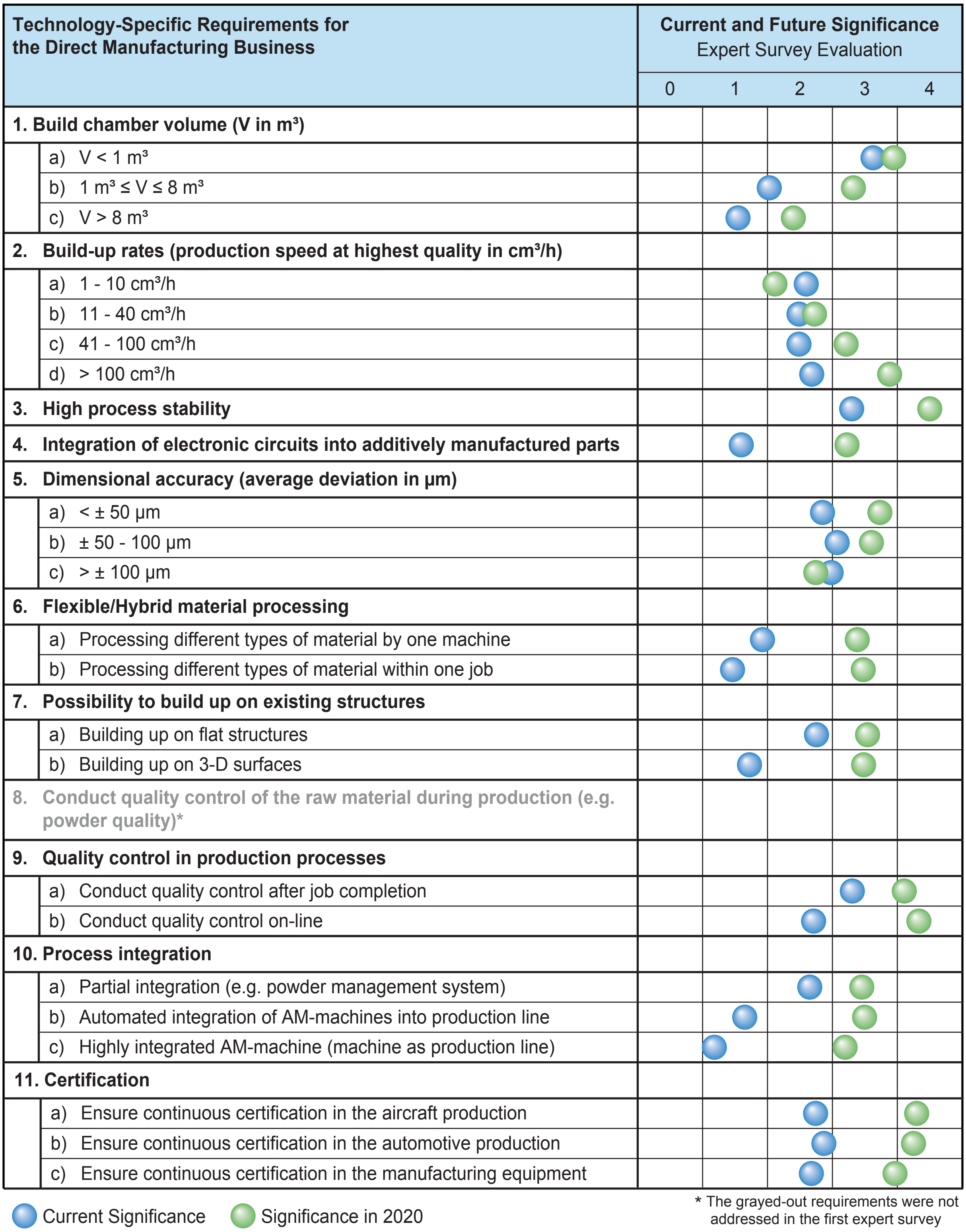
At first glance, the overall assessment shows that the significance of all listed technology-specific requirements will increase in future. The most significant requirements are:

- **High process stability** (No. 3) is assessed to be an outstanding requirement for the penetration of AM in the future.
- A **database containing properties of AM-materials** (No. 17) is also of enormous importance today and will continue to be so in future.
- With regard to the quality control in production processes, today reliable **quality control process after job completion** (No. 9a) play a larger role than on-line control processes (No. 9b). However, the experts believe that **on-line quality control processes** will be crucial for a broad application of AM in the future.
- **Continuous certification** is not only of major importance for the aircraft and automotive production, but also plays a vital role for the electronics manufacturing equipment.
- **Design rules** (No. 16) and **recyclability of materials** (No. 14) are further particularly significant requirements for the current and future business of AM.
- Regarding new materials and material properties, especially the **processability of carbon-fiber-reinforced polymers** (No. 12b) and **fire resistance of AM-materials** (No. 13a) are judged to become important in the future, respectively.
- With regard to the quantifiable requirements, it is noticeable that the requirements on AM-machines with larger **build-chamber volumes** (No. 1b, 1c) are not ranked as high as the requirements on higher **build-up rates** (No. 2), better **surface quality** (No. 3) or higher **dimensional accuracy** (No. 5).
- Furthermore, **lower maintenance costs** (No. 7) are judged as more important than **lower machine incidental acquisition costs** (No. 6).

Largest deviation between current and future significance for processing different materials within one job and building on 3-D surfaces.

According to the experts' assessment, a large number of requirements will have a medium significance in the future. As their current significance is ranked as rather negligible today, these are requirements with the largest deviations between the current and future significance. Some exemplary requirements with large deviations related to machine ability are listed in the following:

- Processing of different types of material within one job (No. 6b),
- Ability of AM-machines to build-up on 3-D surfaces (No. 7b),
- Processing shape memory alloys (No. 12d),
- Automated integration of AM-machines into existing production lines (No. 10b) and
- Highly integrated AM-machines (No. 10c).



* The grayed-out requirements were not addressed in the first expert survey

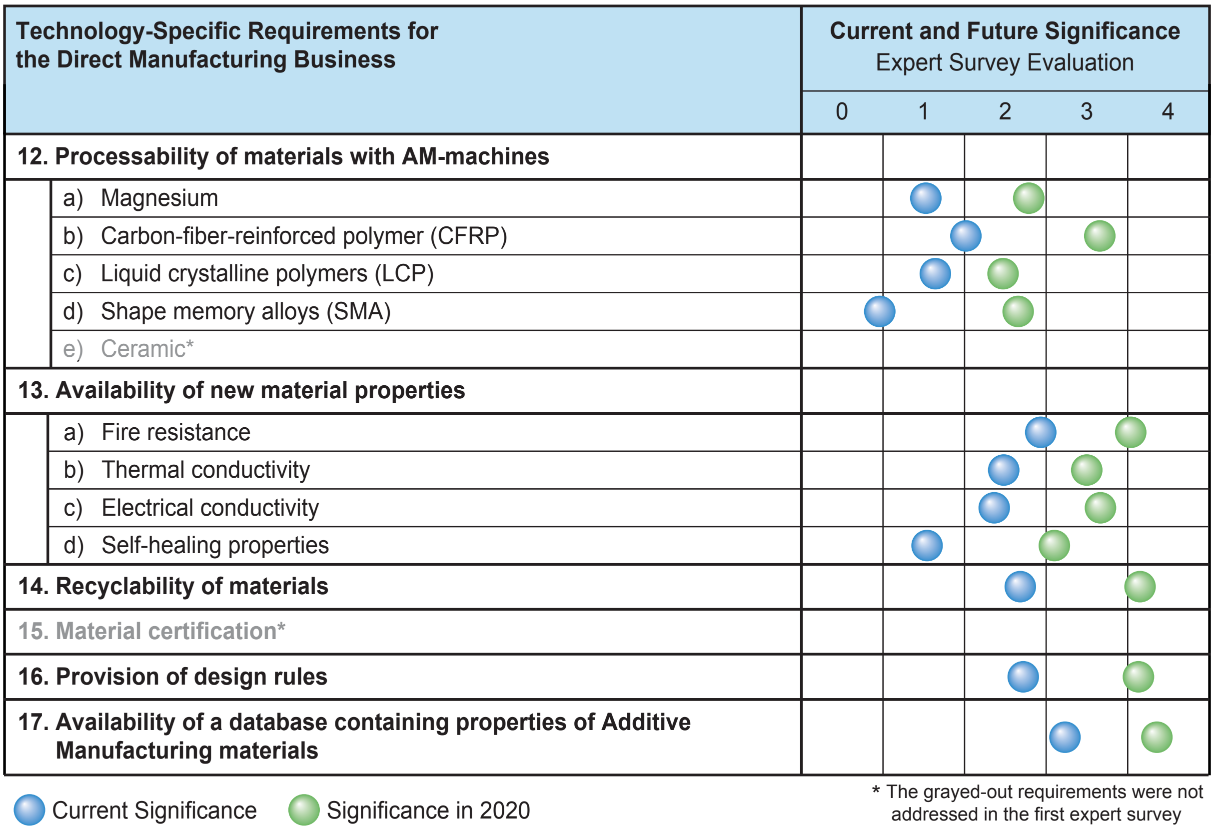


Figure 3-4: Current and future significance of technology-specific requirements

All in all, it is striking that there are considerable discrepancies between the requirements deduced from developed innovation fields and the experts' assessment of the requirements' significance. A large number of the requirements, that are crucial for the realization of many applications, seem to be of minor importance from the experts' perspective.

For instance, a larger *build-chamber volume* is required for the realization of a large number of application ideas developed for the aerospace or automotive industry, e.g. in the innovation fields *Morphing Structures* or *Functional Body-in-White*. However according to the experts, a *build chamber volume* sized larger than 8 m^3 (No. 1c) is not expected to be significant for the future AM-business.

Technology-specific requirements show an overall increase in significance from today to 2020. High process stability, a database containing properties of AM-materials, on-line quality control processes, continuous certification and design rules are outstanding for the penetration of AM in the future. For an automated integration of AM-machines into existing production lines and highly integrated AM-machines, the current and future significance substantially deviate.

3.1.3 Evaluation of Technologies' Degree of Performance

In a second step, the experts were asked to estimate the performance of selected technologies regarding each requirement (degree of performance) on a scale from "0" (i.e. there is a call for action) to "4" (i.e. the technology has got a distinctive strength concerning this requirement). Consolidating the results for the significance and the performance, the need for action for further development and optimization of the technology in accordance with (possible) future applications can be deduced.

Therefore, the arithmetic mean is determined for both, the (current and future) significance of the requirements and the performance of the technologies. Based on this, each requirement is positioned in a significance-performance portfolio, as shown in extracts in the following figures. The confidential study comprises detailed results.

In the significance-performance portfolio, the ordinate intercept shows the significance of the requirements; the abscissa intercept indicates one technology's degree of performance regarding the requirements. In the portfolio, three areas can be distinguished:

- Critical requirements – red area: These requirements are of high significance for the business; the technology's performance regarding these requirements is weak. Critical requirements indicate an immediate need for action.
- Balanced requirements – green area: The significance of these requirements corresponds to the technology's performance regarding these requirements.
- Over-emphasized requirements – yellow area: One technology's performance is distinctively strong regarding the requirements, although these requirements are of low significance for the (future) business.

The following section presents the significance-performance portfolios for the technologies that were addressed in the survey/project.

Fused Layer Modeling Technologies (e.g. Fused Deposition Modeling)

FLM Technologies partly meet future requirements.

Figure 3-5 shows an excerpt from the significance-performance portfolio for Fused Layer Modeling (FLM) Technologies. The evaluation of the survey results shows that FLM Technologies meets all of the listed requirements today. For instance, in contrast to Powder Bed Fusion Metal Technologies, the *build chamber volume (No. 1)* is non-critical and needs only little adaption to fit the future significance.

Even more, the current technology performance is sufficient to meet some of the future requirements, such as the *fire resistance of applied materials (No. 13a)*. However, to realize a correlation between the technology's performance and significance of the requirements in the future, the technology's performance needs to be improved concerning many requirements.

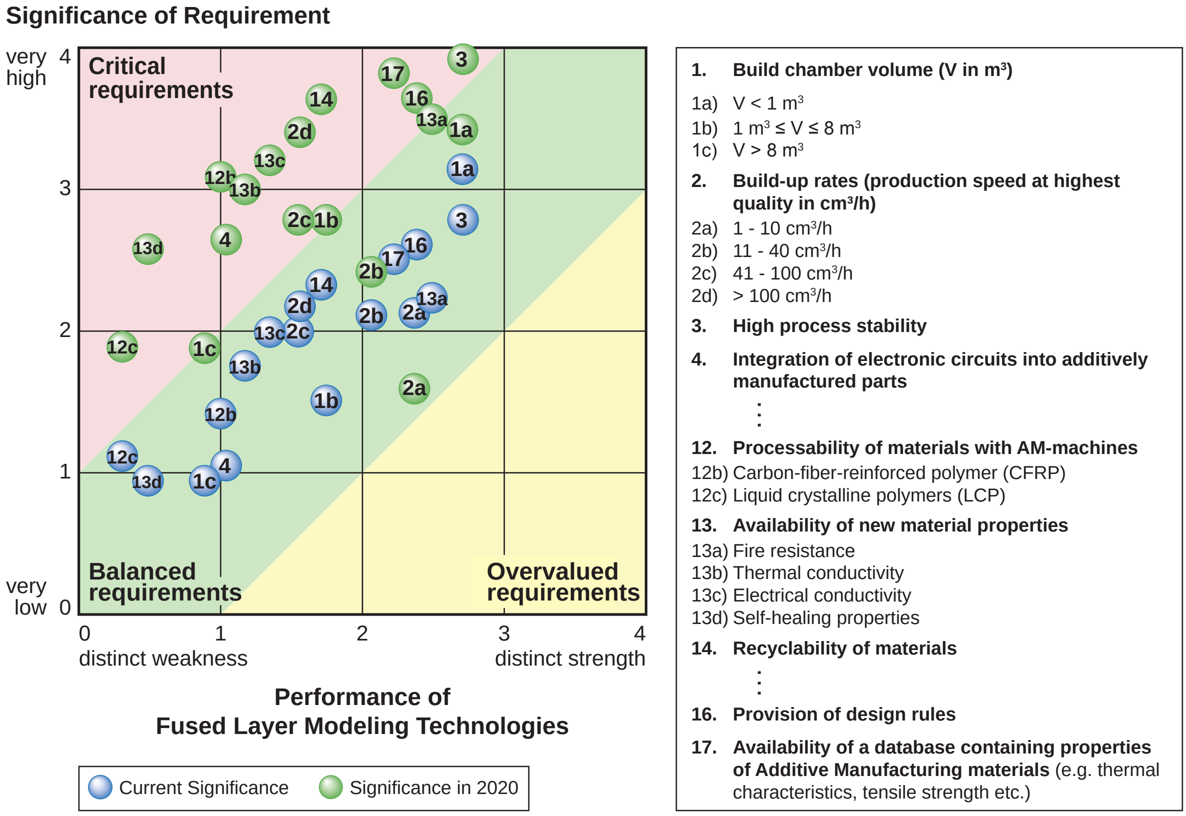


Figure 3-5: Extract from significance-performance portfolio for Fused Layer Modeling Technologies (e.g. Fused Deposition Modeling)

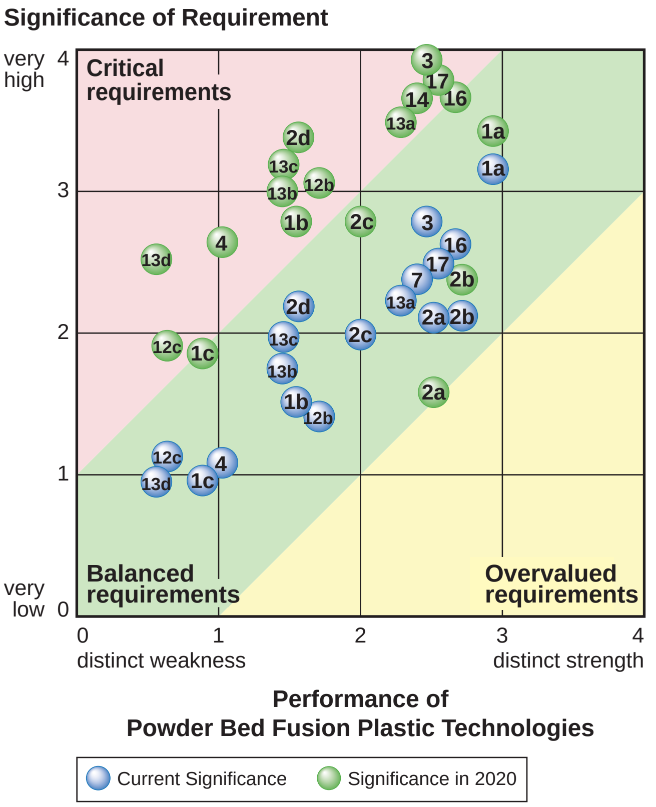
In the future, research is required with regard to recyclability and new properties of AM-materials for FLM Technologies.

The future competitiveness of FLM Technologies will inter alia depend on the *recyclability of materials (No. 14)* and the *availability of new material properties (No. 13)*. Especially, *self-healing material properties (No. 13d)* need to be pushed in order to meet the requirements for the business of tomorrow. Research is also required regarding the *processability of carbon-fiber-reinforced polymers (No. 12b)*, as the significance of this requirement is expected to be very high in the future. Furthermore, according to the experts' assessment, effort is still needed to meet the future requirements on higher *build-up rates (No. 2d)*.

Powder Bed Fusion Plastic Technologies (e.g. Selective Laser Sintering)

Today, Powder Bed Fusion Plastic Technologies largely meet the requirements.

Figure 3-6 shows an excerpt of the significance-performance portfolio for Powder Bed Fusion Plastic Technologies. The evaluation of the survey results shows that from today's point of view, the significance of the requirements largely correlates with the technology's performance. This can be deduced from the position of the blue bullets, which are almost exclusively located in the green area of the portfolio. In future however, the vast majority of the requirements will gain significance. Thus, they are likely to turn into *critical requirements* if no technological advances will be achieved.



1. **Build chamber volume (V in m³)**
1a) V < 1 m³
1b) 1 m³ ≤ V ≤ 8 m³
1c) V > 8 m³

2. **Build-up rates (production speed at highest quality in cm³/h)**
2a) 1 - 10 cm³/h
2b) 11 - 40 cm³/h
2c) 41 - 100 cm³/h
2d) > 100 cm³/h

3. **High process stability**

4. **Integration of electronic circuits into additively manufactured parts**

⋮

12. **Processability of materials with AM-machines**
12b) Carbon-fiber-reinforced polymer (CFRP)
12c) Liquid crystalline polymers (LCP)

13. **Availability of new material properties**
13a) Fire resistance
13b) Thermal conductivity
13c) Electrical conductivity
13d) Self-healing properties

14. **Recyclability of materials**

⋮

16. **Provision of design rules**

17. **Availability of a database containing properties of Additive Manufacturing materials** (e.g. thermal characteristics, tensile strength etc.)

Figure 3-6: Extract from significance-performance portfolio for Powder Bed Fusion Plastic Technologies (e.g. Selective Laser Sintering)

In the future, the vast majority of the requirements is expected to turn into critical requirements.

The requirement *build-up rates > 100 cm³/h (No. 2d)* is already considered as almost critical today. Research that contributes to the production speed could promote Powder Bed Fusion Plastic Technologies in the future.

The amount of research that has to be conducted to meet a requirement sufficiently can be approximated by the horizontal distance between its position in the future and the left delimiting line of the *balanced requirements*. For example, an adequate *availability of materials with self-healing properties (No. 13d)* requires much more effort in development than increasing *process stability (No. 3)* to a sufficient level. In contrast, requirements like *build chamber volume < 1 m³ (No. 1a)* are already matched comparably well and will, if at all, require only low effort to suit future requirements.

Powder Bed Fusion Metal Technologies (e.g. Selective Laser Melting)

Figure 3-7 shows an excerpt of the results for Powder Bed Fusion Metal Technologies. According to the experts, some future requirements can already be fulfilled sufficiently by the technology today. This implies that regarding these requirements, e.g. *recyclability of materials (No. 14)*, the market demand for improvements is low. Even though, with regard to *build-up rates (No. 2)*, major advancements are required.

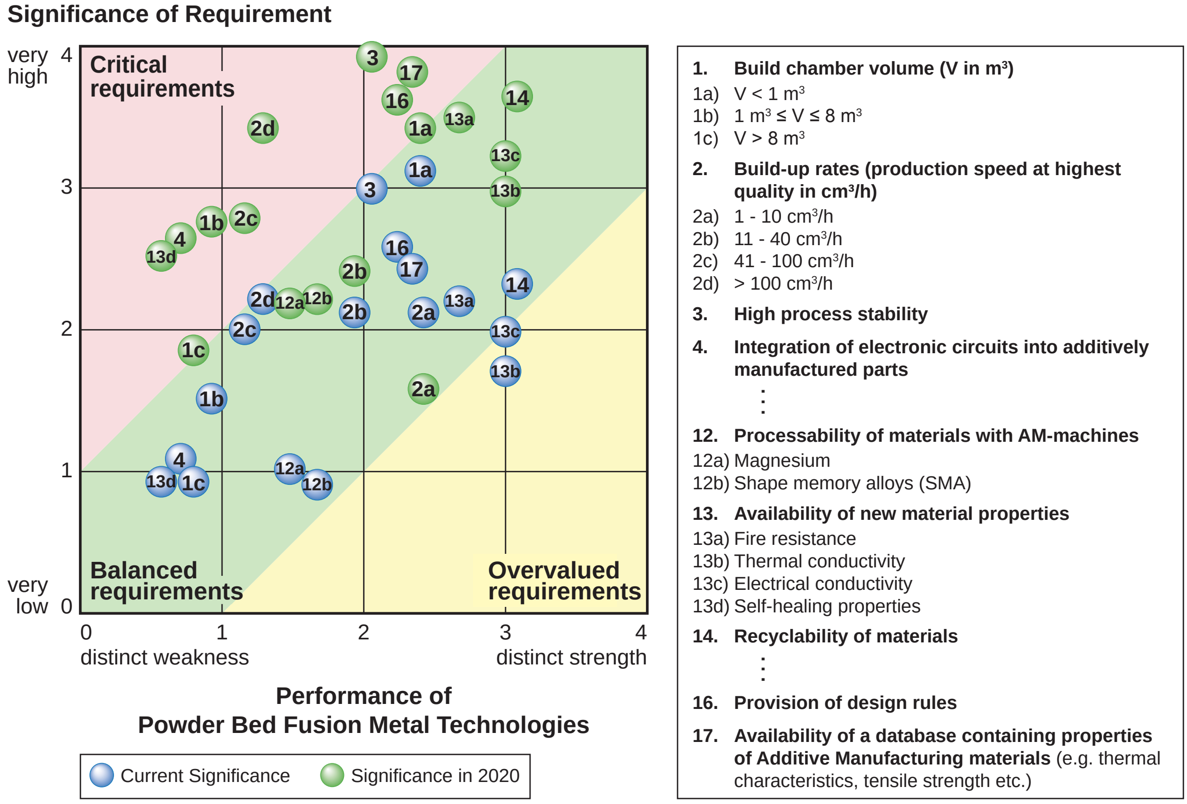


Figure 3-7: Extract from significance-performance portfolio for Powder Bed Fusion Metal Technologies (e.g. Selective Laser Melting)

Process stability is assessed as almost critical today.

In contrast to the expert's assessment of Powder Bed Fusion Plastic Technologies, the *process stability (No. 3)* of Powder Bed Fusion Metal Technologies is judged as almost critical today and needs to be improved continuously.

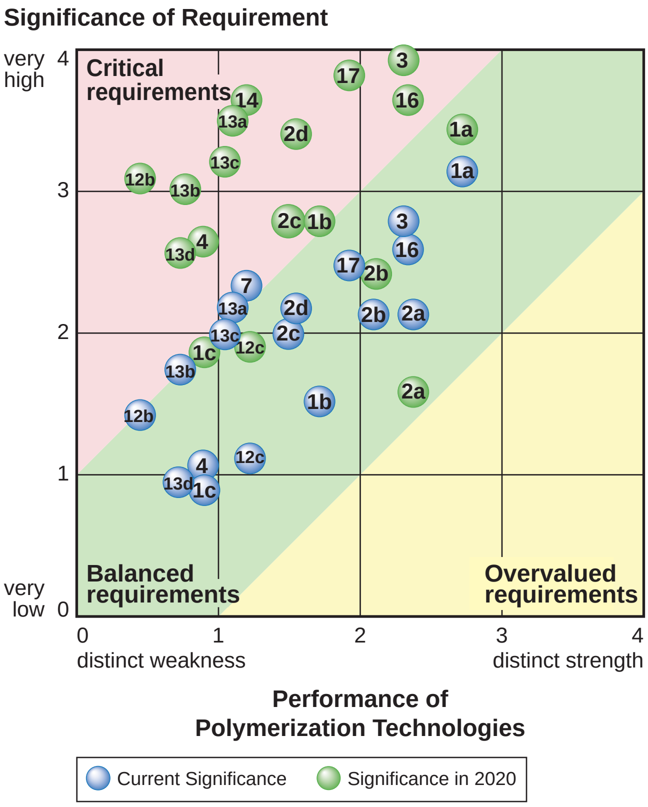
Special attention needs to be paid to the *build chamber volume (No. 1)*. As the significance for a *build chamber volume between 1 m³ and 8 m³ (No. 1b)* is assessed to be highly significant for the year 2020, further research in this area might be beneficial. Regarding the *availability of new material properties (No. 13)*, the significance of *self-healing properties (No. 13d)* is expected to be high in the future. To keep Powder Bed Fusion Metal Technologies competitive in the future, further research that contributes to the availability of self-healing material properties should be pushed. A contrary strategy needs to be pursued with regard to *materials featuring thermal or electrical conductivity (No. 13b, No. 13c)*, as the future significance correlates with the current technology performance.

Requirements on material properties such as thermal and electrical conductivity are already well met.

Polymerization Technologies (e.g. Stereolithography)

Some requirements are already critical today for Polymerization Technologies.

Figure 3-8 shows an excerpt of the significance-performance portfolio for Polymerization Technologies. The evaluation of the survey results shows that the correlation between the technology's performance and the significance of the selected requirements is the lowest of all considered technologies. Even for today, five requirements are assessed as critical.



1. Build chamber volume (V in m³)
1a) V < 1 m³
1b) 1 m³ ≤ V ≤ 8 m³
1c) V > 8 m³

2. Build-up rates (production speed at highest quality in cm³/h)
2a) 1 - 10 cm³/h
2b) 11 - 40 cm³/h
2c) 41 - 100 cm³/h
2d) > 100 cm³/h

3. High process stability

4. Integration of electronic circuits into additively manufactured parts

⋮

12. Processability of materials with AM-machines
12b) Carbon-fiber-reinforced polymer (CFRP)
12c) Liquid crystalline polymers (LCP)

13. Availability of new material properties
13a) Fire resistance
13b) Thermal conductivity
13c) Electrical conductivity
13d) Self-healing properties

14. Recyclability of materials

⋮

16. Provision of design rules

17. Availability of a database containing properties of Additive Manufacturing materials (e.g. thermal characteristics, tensile strength etc.)

Figure 3-8: Extract from significance-performance portfolio for Polymerization Technologies (e.g. Stereolithography)

To increase future competitiveness of Polymerization Technologies, material availability and processability need to be improved.

The performance of Polymerization Technologies lacks when it comes to the *processability of carbon-fiber-reinforced polymers (No. 12b)* or the *availability of new material properties (No. 13)*. Furthermore, the *recyclability of materials (No. 14)* is marked as a critical requirement of today. Looking into the future, it stands out that every requirement that is already critical today will become especially critical in the future, as the significance of almost all requirements is indicated to increase. In order to remain competitive, research in the area of material availability and material processability needs to be pushed significantly. The application of Polymerization Technologies in the future also depends on the *availability of a database containing properties of AM-materials (No. 17).*The requirements *build chamber volume (No. 1)* and *build-up rates (No. 2)* are uncritical today as well as in the future, as the technology's performance largely correlates with the requirements' significance. Here, just slight technology advancements are needed.

The considered technologies are basically balanced, as they – in principle – fulfill today's requirements well. Only few requirements are critical. However, due to the overall tendency to increased significance in the future, most requirements demand for advancements of AM-technologies to achieve a correlation between the requirements' significance and the performance of the technologies.

3.2 Innovation Roadmapping of Required Advancements

Based on the results of the first survey, a second survey was conducted. The main purpose of the survey was the get a sound overview on the point in time when – from AM-experts' point of view – the selected requirements will be fulfilled by selected AM-technologies. This allows the creation of innovation roadmaps, indicating when the identified requirements will be fulfilled. The expert survey is available in the appendix A2.

Structure and Proceeding in Expert Survey 2

Wide ranging expertise of participants

The survey was conducted in 2 languages in the period from June until November 2012. To reflect the opinion of the entire AM-industry, the survey addresses AM-experts along the whole value chain ,e.g. AM-machine manufacturers and material suppliers, users of AM-technologies (OEMs and suppliers) as well as universities and research facilities dealing with AM-technologies. The survey was sent to **395 AM-experts**; **75 experts (19%)** participated in the survey.

The survey is divided into three parts: *General Information*, T*echnology-Specific Requirements* and *Final Statements*. The first part addresses the professional background of the experts. In the second part, the survey asked the experts to estimate the point in time when the selected requirements will be met by selected AM-technologies. This data allows creating innovation roadmaps. These indicate when the identified future applications can be manufactured, as technological requirements will be fulfilled. In the following, these results are presented in extracts; detailed results are part of the confidential study.

3.2.1 General Information

This chapter addresses the composition of the participants and general (anonymous) information about their professional background. Therefore, the experts were asked to indicate their field of activity, e.g. part of the value chain of AM and the company division they are working in. The percentage distributions are shown in figure 3-9 and 3-10 (Note: multiple choices possible).

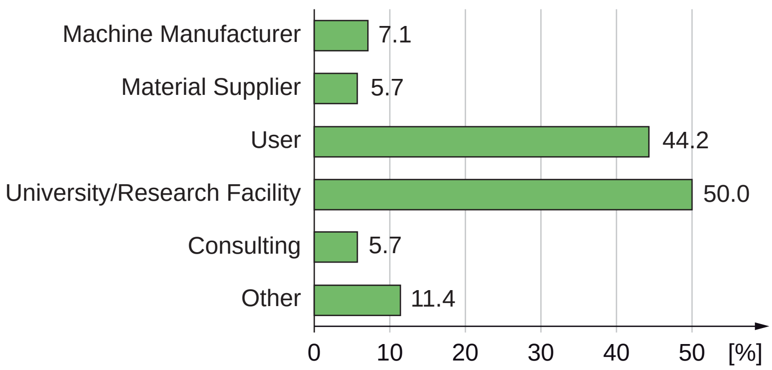


Figure 3-9: Part of the value chain the participants are working in (in percentage terms)

With a share of 50% and 44%, the research facilities and users of AM respectively count the largest share among all participants, followed by machine manufacturers, material suppliers and consulting facilities. The *Other* category includes participants that do not fit into the listed categories.

Majority of the participants are research facilities and users of AM.

Figure 3-10 also illustrates the heterogeneous composition of the participants: the range covers all company divisions. The vast majority of the participants (74%) specify to work in research and development. With 23% and 14%, respectively the management division and the sales division also comprise a relatively large proportion. The other listed company divisions were named by about 3%-12% of the participants.

Most participants are active in research and development.

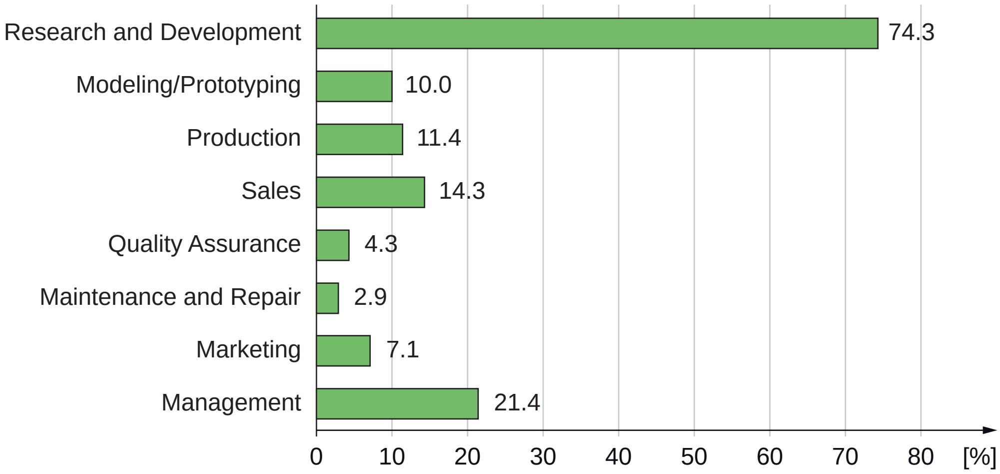


Figure 3-10: Company divisions the participants are working in (in percentage terms)

The bar chart in figure 3-11 illustrates in percentage terms how the population of all participants uses AM (Note: multiple choices possible). The majority of the participating experts (79%) indicate to use AM for Direct Manufacturing. The usage of AM for Rapid Prototyping and Rapid Tooling are common to respectively 64% and 31% of the participants. This correlates with the fact that the majority of the participants indicated to work in research and development, see figure 3-10.

The usage of AM for the production of end-use parts is widely spread among the participants.

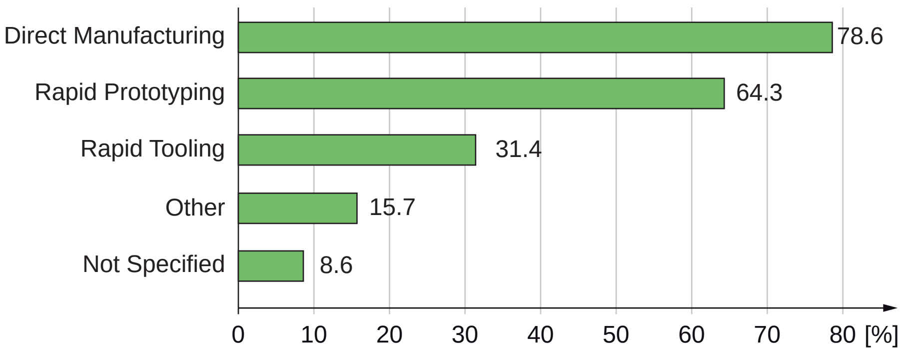


Figure 3-11: Usage of AM-technologies (in percentage terms)

3.2.2 Innovation Roadmapping – Fused Layer Modeling Technologies

Innovation roadmap depicts the maturity level of the requirements.

The innovation roadmap for Fused Layer Modeling (FLM) Technologies, depicted in figure 3-12, shows an excerpt of the underlying data that collected in the expert survey. It illustrates the time at which technology-specific, material-specific and general requirements are expected to be met by this technology. In the horizontal, the technology-specific, material-specific and general requirements are listed. The time axis indicates when the requirements are expected to be realized. Detailed results are part of the confidential study.

Regarding the *build chamber volume (No. 1)*, the experts assess that objects requiring a comparably small *build chamber volume (1 m³ to 2 m³)* can be realized with FLM Technologies by 2015. Machines with a *build chamber volume of up to 8 m³* are expected to be available in 2019. After two more years even bigger volumes should be available.

Increasing buid-up rates is a core challenge for future research.

An increased build chamber volume automatically requires faster *build-up rates (No. 2)* during the process. According to the survey results, a *production speed of up to 120 cm³/h* will be possible by 2016. Higher build-up rates still require high effort in research and development. The experts expect *production speeds of 150 cm³/h* by 2020. Even higher build-up rates will be possible by 2023 at the earliest. Hence, increasing build-up rates is one of the core requirements – tackling this challenge is expected to pose a time-consuming task.

The deviation of reproducibility, defining a *process stability (No. 3) of 0.5% and 0.1 %*, in this context, is expected to be achieved in 2016 and 2020 respectively. A further technology-specific requirement is the *integration of electronic circuits (No. 4)* into additively manufactured parts, which is expected to be realized from 2017 on. By this time, most *material-specific requirements (No. 12)* will be met as well. The processability of *carbon-fiber-reinforced polymers* and *liquid crystalline polymers* can be realized by 2017 and 2020, respectively.

Fire resistance or electrical/ thermal conductivity are expected by 2016.

Materials with new properties (No. 13), such as *fire resistance*, *thermal/electrical conductivity* or *recyclability* are assessed to become available in 2016. More effort is expected to be put in developing materials with *self-healing properties*. They will be available by 2023 at the earliest. General requirements, e.g. the *provision of design rules (No. 16)* and the *availability of a database containing properties of AM-materials (No. 17)*, are easier to meet and are therefore expected to be fulfilled by 2015.

Innovation roadmaps show the interrelation between applications and mandatory requirements.

The innovation roadmap can be used for roadmapping of future applications. Therefore, an application is orthogonally positioned at the earliest possible date of realization of its enclosed requirements on DM. Thereby, the roadmap provides information when the applications can be realized, as the technology will have reached the required performance. These results are accessible for DMRC partners only.

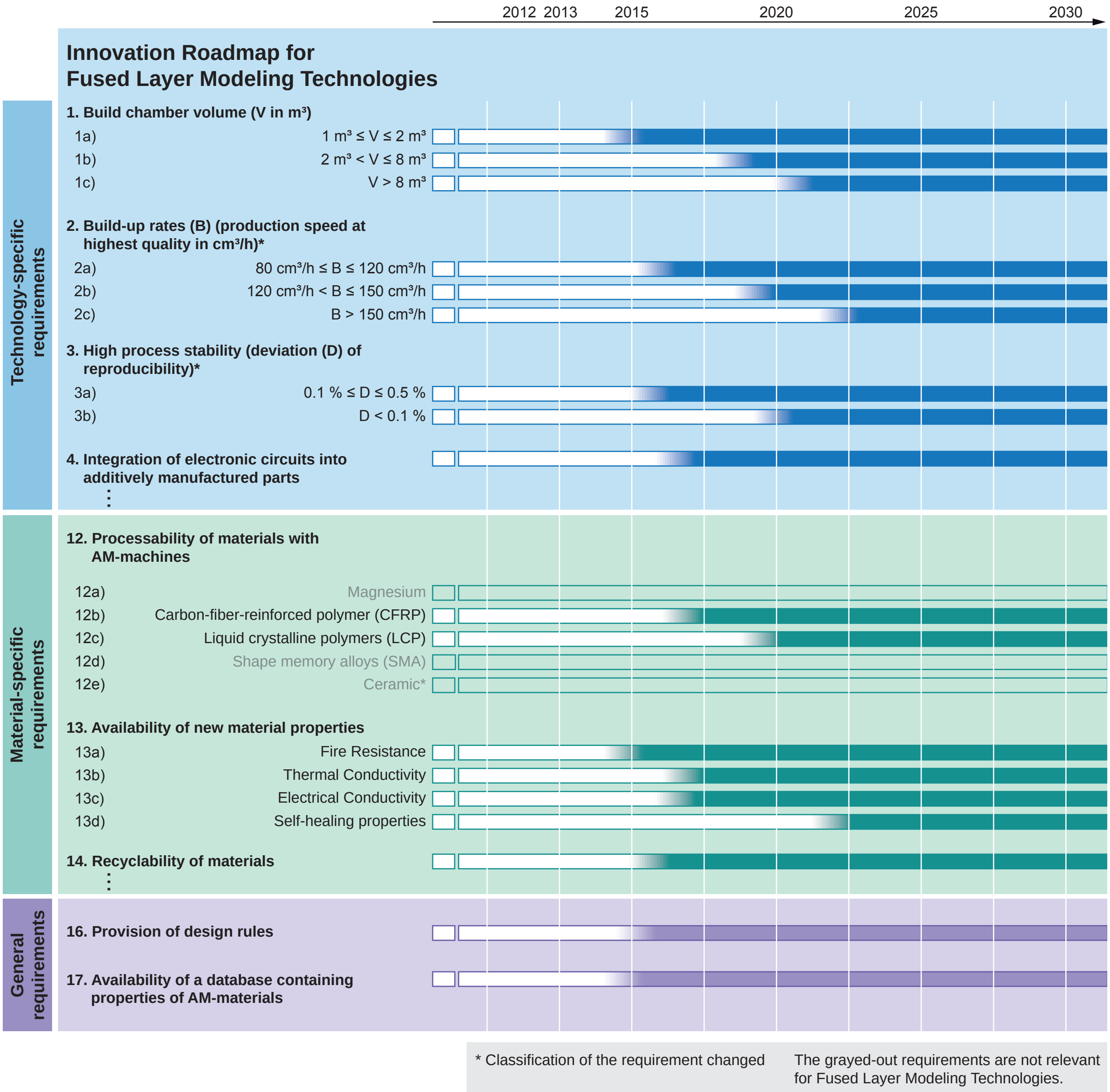


Figure 3-12: Extract from Innovation Roadmap for FLM Technologies (e.g. Fused Deposition Modeling)

For FLM Technologies the experts expect the most of the listed requirements to be fulfilled by 2020, except high build-up rates and the availabililty of self-healing properties. The general requirements may already be met in a few years. This also counts for selected material properties, e.g. electrical/ thermal condictivity

3.2.3 Innovation Roadmapping – Powder Bed Fusion Plastic Technologies

Innovation roadmap indicates the maturity level of the requirements.

The innovation roadmap in figure 3-13 presents an excerpt of the survey's results for Powder Bed Fusion Plastic Technologies, indication when selected technology and material-specific and general requirements are expected to be met. Detailed results are part of the confidential study that is accessible for DMRC partners only.

At a first glance, this innovation raodmap shows that the technology specific requirements are expected to be met earlier than for POwder Bed Fusion Metal Technologies, compare to figure 3-14. Technology related requirements are e.g. the *build chamber volume (No. 1)* and the *build-up rates (No. 2)*, specifying the production speed at highest quality in cm^3/h. According to the assessment in the survey, objects with a *volume of 1 m^3 to 2 m^3* may be manufactured from 2016 on; a *volume larger than 8 m^3* is expected to be possible after 2024.

Reliable process stability is expected by 2021.

Regarding the *build-up rates (No. 2)*, the development is expected to be faster. *Build-up rates up to 120 cm^3/h* may be achieved by 2016; more than *150 cm^3/h* in 2022 at the earliest. A *process stability (No. 3) of 0.5% and 0.1 %*, in terms of deviation of reproducibility, is estimated to be realized respectively in 2016 and 2021. The *integration of electronic circuits into AM-parts (No. 4)* may become possible by 2020.

Increasing the maturity level of the *material specific requirements (No. 12)* for the Powder Bed Fusion Plastic Technologies is estimated to take more time than Powder Bed Fusion Metal Technologies. According to the survey, the *processability of carbon-fiber-reinforced polymers* and *liquid crystalline polymers* can be realized by 2017 and 2020 respectively.

Regarding the *available material properties (No. 13)*, *fire resistant materials* will be available by 2015, *recyclable materials* one year later and materials with *electrical conductivity* in 2017. *Self-healing properties* may be realized by 2022. *Design rules (No. 16)* for this technology and a *database containing properties of AM-materials (No. 17)* are expected to be already accomplished in 2016.

Innovation roadmaps give hints on conceivable realization date for future applications.

This innovation roadmap is also a helpful tool for roadmapping of future applications, providing the decision maker information when future applications can be realized, as the technology-specific, material-specific and general requirements will have reached the required maturity level.

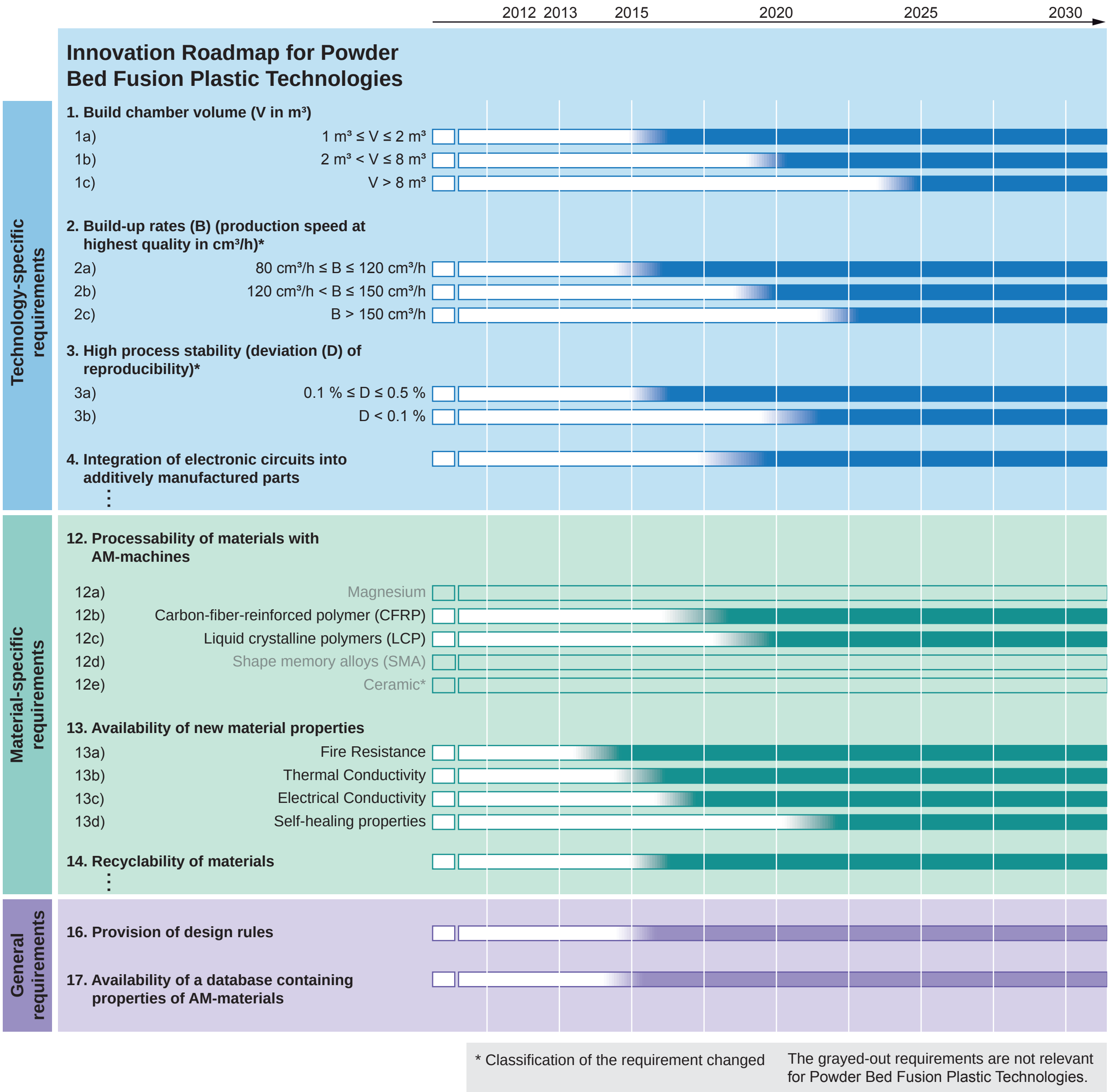


Figure 3-13: Extract from the Innovation Roadmap for Powder Bed Fusion Plastic Technologies (e.g. Selective Laser Sintering)

Powder Bed Fusion Plastic Technologies are expected to meet the majority of the listed requirements by 2020. Larger build chamber volumes, higher build-up rates and self-healing material properties are assessed to be met in the further future. Some material properties and general requirements may be fulfilled already in 2016.

3.2.4 Innovation Roadmapping – Powder Bed Fusion Metal Technologies

Technology-specific requirements are critical.

The innovation roadmap for Powder Bed Fusion Metal Technologies depicted in figure 3-14 outlines an extract of the survey's results on the date of realization of technology and material-specific and general requirements. All data are available in the confidentail study. At a first glance, it becomes obvious that the technology-specific requirements are critical points for these technologies. A *build chamber volume* (No. 1) of more than *8 m³* is not expected to be realized before 2027. Even a moderate volume of *1 m³ to 2 m³* may merely become available by 2020, which is six years after the corresponding availability for FLM or Polymerization Technologies, compare figure 3-12 and 3-15.

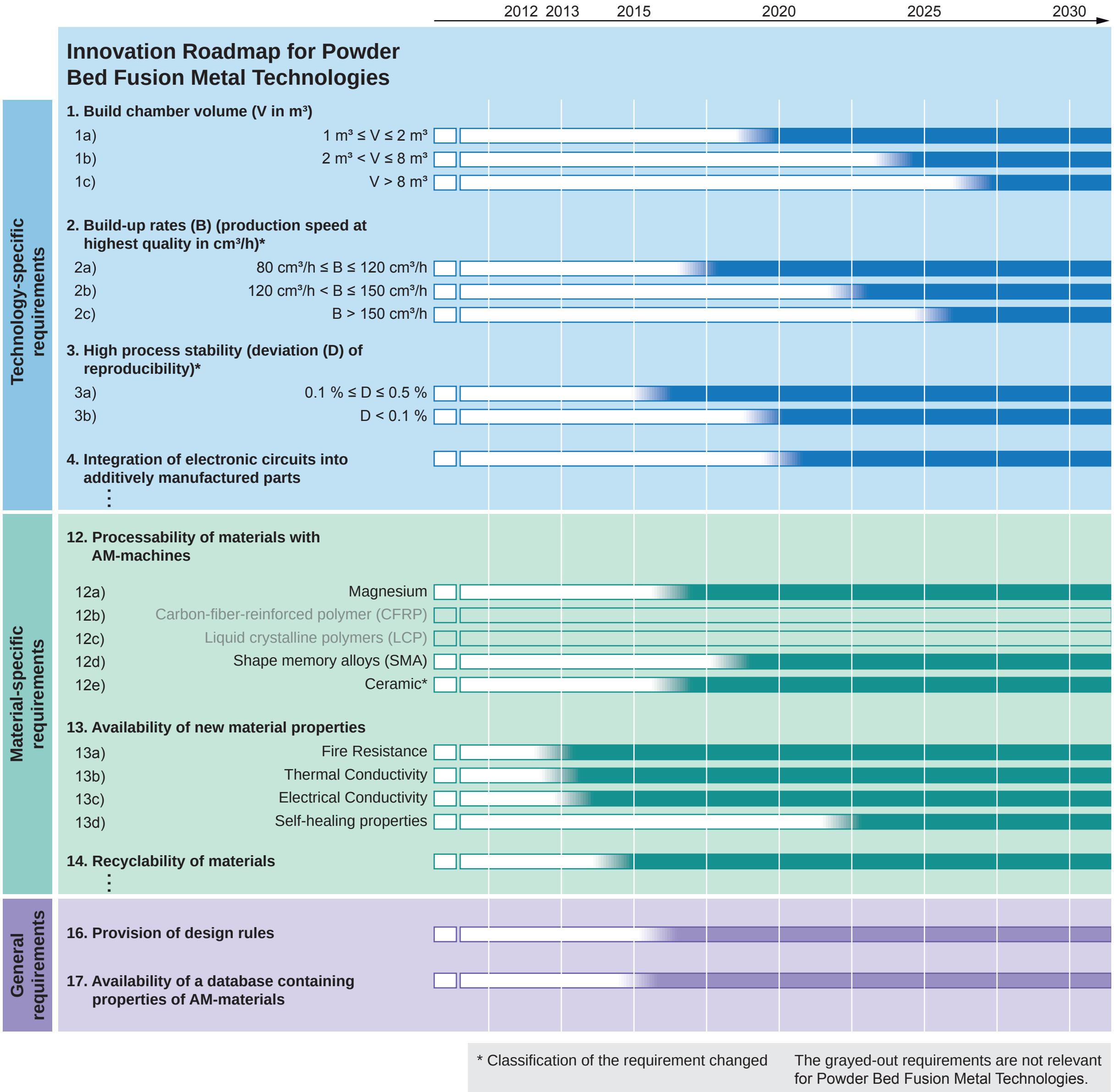


Figure 3-14: Extract from the Innovation Roadmap for Powder Bed Fusion Metal Technologies (e.g. Selective Laser Melting)

In a similar matter, the development of *build-up rates (No. 2)* is expected to proceed more slowly for Powder Bed Fusion Metal technologies. A production speed up to *120 cm³/h* is expected to be possible by 2018; more than *150 cm³/h* will be reached by 2026 at the earliest. A *process stability (No. 3)* of *0.5% and 0.1 %*, in terms of deviation of reproducibility, may be realized respectively by 2016 and 2021. Using this technology, *electronic circuits (No. 4)* can presumably be integrated into additively manufactured parts by 2020 – once again significantly later than in case of FLM or Polymerization Technologies.

Material-specific requirements can largely be met by 2020, except self-healing material properties.

In contrast to the technology-specific requirements, the *material-specific requirements* are estimated to be met comparably early. The *processability of magnesium* and *shape memory alloys (No. 12)* may respectively become possible in 2016 and 2018. *Fire resistant materials (No. 13)* are expected to be available in 2013, *recyclable materials (No. 14)* 2015. The implementation of *self-healing properties (No. 13)* will last until 2023, quite as long as with other technologies.

Design rules (No. 16) and a *database containing properties of AM-materials (No. 17)* are expected by 2016.

Technology-specific requirements are assessed to be critical for Powder Bed Fusion Metal Technologies. This applies in particular for a larger build chamber volume. The vast majority of the listed material properties may be fulfilled within this year, except self-healing properties.

3.2.5 Innovation Roadmapping – Polymerization Technologies

Figure 3-15 shows an excerpt from the innovation roadmap for Polymerization Technologies. The development of the technology-specific requirements is similar to the previous roadmap. From 2014 on, a *build chamber volume (No. 1) of 1 m³ to 2 m³* is expected to be realized. By continuous research, the build chamber volume can be extended gradually to more than *8 m³* by 2021.

The *build-up rates (No. 2)* again take more time to meet the requirements. Production speeds up to *120 cm³/h* will be reached by 2017. Generating objects faster than *150 cm³* in an hour will be possible from 2023 on. This clearly shows that this requirement poses a great challenge – meeting this will require substantial effort.

The deviation of reproducibility of *0.5% and 0.1 %*, defining the *process stability (No. 3)* in this context, is expected to be achieved in 2016 and 2021, respectively. A further technology-specific requirement is the *integration of electronic circuits into additively manufactured parts (No. 4)*, which is expected to be realized from 2018 on.

Advancement of material-specific requirements requires more effort than for FLM Technologies.

The development of *material-specific requirements* is estimated to require more effort for Polymerization Technologies than for FLM Technologies. New materials *(No. 12)*, e.g. *carbon-fiber-reinforced polymer* and *liquid crystalline polymers* could be used in 2019. *Mate-*

rial properties (No. 13), e.g. *fire resistance*, *thermal/electrical conductivity* or *self-healing properties* will be available in 2019, about two years after their availability for FLM Technologies. *Recyclability (No. 14)* of the utilized materials is expected by 2022. *Design rules (No. 16)* for Polymerization Technologies are assumed to become available from 2018 on, three years later than for FLM Technologies, and a *database containing properties of AM-materials (No. 17)* by 2015 at the earliest.

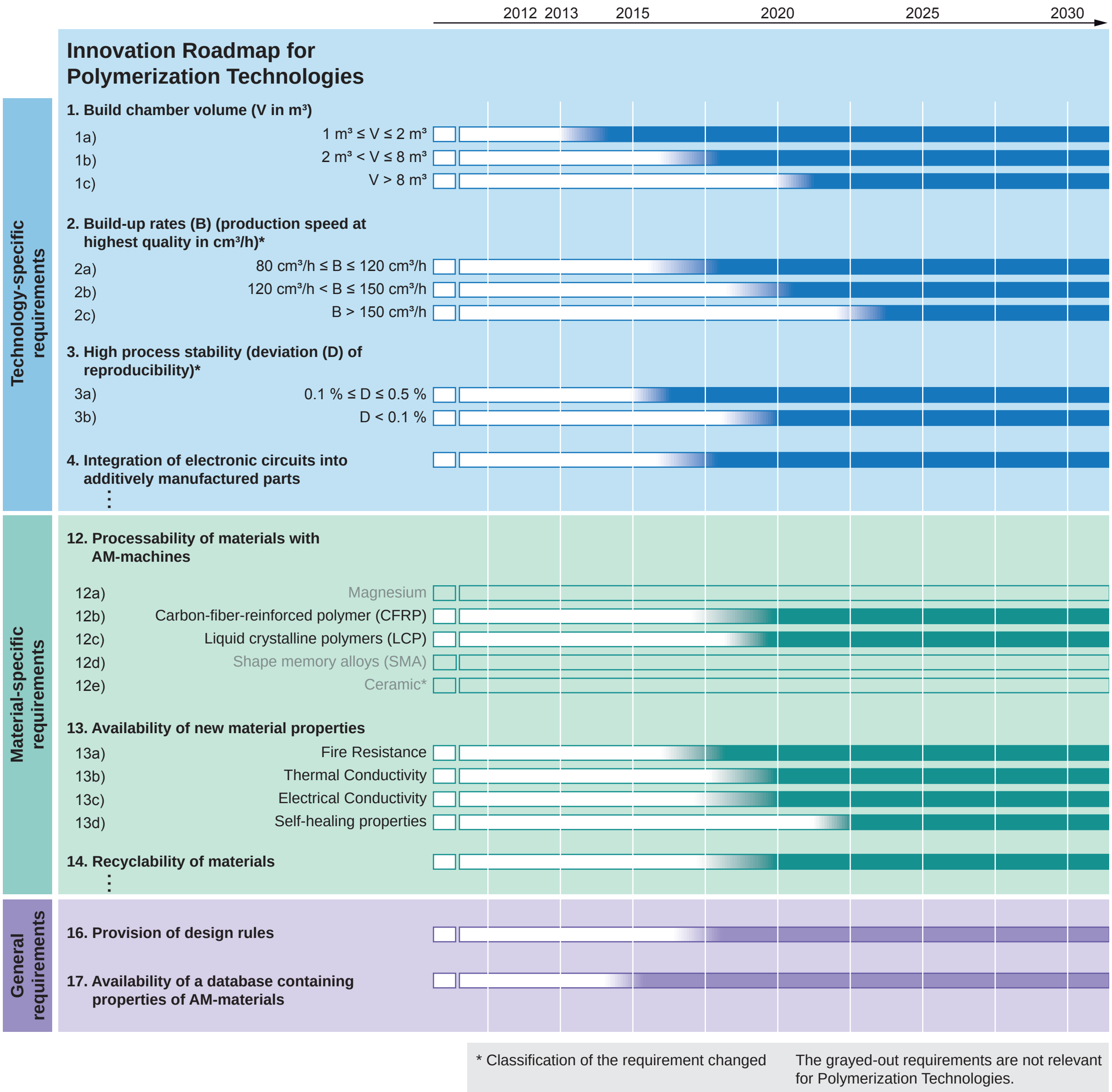


Figure 3-15: Extract from the Innovation Roadmap for Polymerization Technologies (e.g. Stereolithography)

Polymerization Technologies are expected to meet the vast majority of the listed requirements by 2020 at the latest. Machines with larger build chamber volumes and higher build-up rates as well as materials with self-healing properties are estimated to become available in the further future.

3.3 Final Statements and Research Fields of Interest

In addition to the assessment of the requirements on DM-technologies, both surveys asked the experts to indicate fields of research and action that are of great importance for them within the context of AM. In the following section, frequently mentioned research fields are shortly described.

Material Research

Research on new materials and material properties is indicated as an action field of great importance by the vast majority of the participants. New materials as well as qualification of existing materials for AM are expected to increase the capabilities of AM-technologies, and thus to expand the technologies' penetration in industrial application. This counts for the development of new materials, like technical thermoplasts, natural and organic materials, bio-compatible and bio-degradable materials, nanomaterial, or ceramics.

Mentioned aspects related to new or improved material properties range from advanced mechanical properties over transparency properties to thermal (fire) and electrical resistance and isolation properties which are especially important for end-users. Another aspect mentioned relates to accurate and reliable properties of existing materials, e.g. the aging behavior of materials. Material properties could be enhanced by process parameter modification, in terms of improved interaction between process and material. Moreover so-called hybrids – bonds between metal and plastic components with electromechanical functions for e.g. electronic components, but also metal powder mixtures – are other fields of interest. Especially for the toys and jewelry industry, colored materials or parts coated with gold respectively are points of interest.

New/Advanced AM-Technologies

The development of new/advanced AM-machines is indicated to be highly important, e.g. machines with multiple lasers. One challenge AM especially faces is multi-material processing, meaning the usage of several materials on the same machine. Another aspect frequently addressed is attributed to the build size of parts that is limited to the build chamber volume, as well as the reduction of production time, the improvement of the surface quality and the layer thickness. This relates to batch processes, i.e. the production of one part takes the same time as manufacturing a whole batch of parts.

Plug and play machines are point of interest for the usage in remote areas, oil rigs, third world countries or naval ships. Furthermore, the participants indicated the interchangeability of process parameters between different AM machines (of one category) as an important field of action/desirable condition.

Process Optimization

Process optimization regarding aspects such as robustness, reproducibility, machine reliability, reduction of costs etc. is named as an important field of action. This also comprises the enhancement of productivity/throughput for all systems, concurrently maintaining constant part quality. Especially, potential users indicate that the penetration of AM is still limited, as currently AM is just suitable for small series production and prototyping.

In addition, pre/post processing cannot be optimally performed today; set-up times significantly reduce the performance of AM-machines. Other aspects with regard to process optimization are process automatization, optimized data preparation, real-time process monitoring and control. Self-monitoring and self-optimizing processes are indicated to be the next obligatory evolution step to push AM towards DM.

Process Integration

Another important field of research mentioned by the participants is process integration. Process integration refers to the integration of AM-processes into conventional manufacturing processes, and how to fit AM products into the manufacturing chain.

Economic (Process) Efficiency

Many of the respondents addressed the economic efficiency of AM-technologies. Firstly, low-budget AM-machines, and secondly process efficiency are mentioned as important fields of action. In the context of process efficiency, the reduction of (additional) costs is of great importance, e.g. costs for removal of restraints, finishing of parts, material costs, service costs etc.

Design Rules

AM-compatible design is quoted as another major field of action. Particularly noteworthy is that the vast majority of the participants regard (standardized) design rules as a mandatory step to enable AM for DM. New and/or different design rules are required to reconcile part properties that depend on the build structure of one part with the unlimited possibilities of “Freedom of Design”. Great benefits that arise from “Freedom of Design” have an almost unlimited potential to impact every product’s design. For instance, the usage of AM for bionic product designs highly ranks on the participants agenda.

Part Properties

Part properties also constitute a major field of action. Major points of interest are: homogeneous temperature distribution, integrative, functional light-weight structures in multi-material design, lattice structures, prediction and reduction of distortion, just to name a few.

Economic Impact of “Design Optimization”

Development of methods/procedures for the identification of the technology that is appropriate for particular purposes is an essential point of interest. This counts for the selection of a suitable AM-technology, but also may serve as a basis for the decision between a conventional technology and an AM-technology. This includes cost modeling tools (break-even analysis) as well as methods for the calculation/anticipation of a part’s life cycle costs, determining the economic impact “Design Optimization” of part geometry can have on unit costs.

Finishing Techniques

New and improved finishing techniques are regarded as an important action field by the majority of the respondents. The goal is to improve and accelerate AM-processes and to increase qualitative reproducibility of AM-parts that are directly “ready to use” and to reduce additional costs. For example, automated finishing techniques are named as necessary fields of research.

Quality Assurance

For quality assurance there is also a great need for action from the participants’ point of view. In many instances the part quality of additively manufactured parts is still inferior to conventionally manufactured parts. Surface quality, same strength values in all 3 axes, dimensional accuracy, and microstructural analysis during and after the production are some aspects mentioned by the experts.

Especially for end-use parts, dimensional and qualitative reproducibility are indispensable. Long-term static and dynamic properties are also quoted as an important field of research. In this context, in-process online monitoring and quality control procedures as well as Non-Destructive Inspection (NDI) or a quality control with Six Sigma are addressed.

Software Solutions

The link between CAD-models and analysis tools is regarded as an action field of great importance that is mandatory for taking full advantage of AM’s possibilities. Thereby for instance, it would be a great benefit for generating internal structures directly. For example, lattice structures could be calculated and adapted according to various requirements. Simulation software can assist for the design of AM parts and testing the parts under different conditions.

Standardization and Certification

To increase the acceptance of AM, common standards have to be elaborated, like tolerances for AM parts or standard supporting structures. In addition, special requirements of the various industries, e.g. fire resistance of materials/parts, have to be taken into account for certification, which in turn requires a common understanding along the value chain. Furthermore, certification for new materials and new AM-processes is regarded as an important step towards DM.

Supply Base

Supply Base seems to be highly ranked on the participants’ agenda. One central challenge is attributed to the limited quantity of existing service bureaus as well as to the quantity of raw material suppliers. Benchmarking of technology suppliers – different machines/brands and material suppliers – is indicated as a facilitating success factor for increasing market transparency in the field of AM.

Education

Education is especially frequently mentioned as an important aspect. To facilitate educational institutions to access AM-technologies, it is necessary to transfer knowledge in teaching and training qualification. Reciprocally, knowledge from research institutions has to be transferred into practice. Moreover, it is required to make both new and existing AM-users aware of AM's potential and to educate the staff. Especially designers need to realize AM's capabilities, and to be qualified for designing products accordingly to these capabilities.

Open Innovation

Open Source for design, development and manufacturing as well as Cloud Production are named as fields of research that will significantly gain in importance for both, machine manufacturers and material suppliers. This may be an appropriate way for a collaborative development of new processes and material between technology suppliers and technology end-users. An "App Store" for software and designs may be a solution for exchanging process parameter apps and files.

Future Research and Interest

To increase the penetration of AM, future research in the field of AM, meaning investments in R&D, facilities and skills, needs to be aligned with market and industry needs. Therefore, developments of existing and untapped business areas have to be anticipated in order to early identify success potentials for future business and to develop ways to timely exploit these potentials. Quoted fields of interest are: concept model realization for macro testing of micro-electromechanical systems (MEMS), devices concepts (micro and mesoscale), applications for aircraft interior, air ducts, medical applications, components for the energy and agriculture sector, and specific tools with a relatively low number of actuation mechanisms that are generally produced in small-volumes and have to be rapidly available. Further fields of interest are: recyclability of AM-products, organ development and cell deposition as well as AM-technologies at the micro- and nanoscale.

3.4 Summary

The Heinz Nixdorf Institute and the Direct Manufacturing Research Center conducted an expert survey on current and future requirements on DM-technologies. The object was to identify the requirements that are mandatory to enable AM for DM, and to determine AM-technologies' performance concerning these requirements. Highly significant requirements, concurrently with a low performance of the technologies, indicate an immediate need for action for the future business.This enables the AM-industry to bundle available competencies to advance AM to DM effectively. The assessment of the technology-specific requirements shows that:

- The vast majority of the requirements will gain in significance.
- High process stability, a database containing properties of AM-materials, on-line quality control processes, continuous certification and provision of design rules are assessed to be outstanding for the penetration of AM in the future.

The requirements with the largest deviations between the current and future significance are the following:

- Ability of AM-machines to process different types of materials within one job,
- Building up on 3-D surfaces,
- Provision of additively processible shape memory alloys,
- Automated integration of AM into existing production lines,
- Highly integrated AM-machines.

Especially for these requirements, there is a need for action. According to the experts some requirements, e.g. a build chamber volume sized larger than 8 m^3, are of minor significance, although these are mandatory for the realization of a many applications developed for the aerospace and automotive industry. All in all, the significance of the technology-specific requirements largely correlates with the technologies' degree of performance across all considered technologies. As the significance of most requirements is expected to increase in the future, the majority of the requirements are likely to turn into critical requirements if no technological advances will be achieved.

Many requirements are expected to become critical if no technological advancements will be realized.

Finally, innovation roadmaps were created for the considered technologies. The time axis indicates when the requirements, that were deduced from the innovation fields, will be fulfilled. With regard to the listed requirements in chapter 3.2, the considered technologies are expected to meet the vast majority of the listed requirements by 2020. The general requirements, e.g. design rules and a database containing properties of AM-materials, are judged to be already met in 2016 on average. Most critical requirements that are estimated to become available after 2022 are:

Most requirements are estimated to be fulfilled by 2020.

- Large build chamber volumes,
- High build-up rates,
- Materials with self-healing properties are estimated to become available in the further future.

The developed innovation roadmaps are a sophisticated tool for strategic product and technology planning: In these roadmaps, the identified applications (chapter 2.2) can be positioned orthogonally at the earliest possible realization date of the requirements that need to be met for the considered applications. Thereby the roadmaps indicate when the applications can be realized as the technology will have reached the required performance. Of course, the presented innovation roadmaps can also be consolidated to an overall innovation roadmap, indication the requirements accross all technologies. All in all, innovation roadmaps allow aligning the technology development with current and future requirements.

Innovation roadmaps as a sophisticated tool for strategic product and technology planning

Especially noteworthy is that in course of our project the vast majority of the research fields of interest, mentioned by the experts, were revealed in terms of requirements on mandatory advancements of AM-technologies.

4

Conclusion and Outlook

The study "Thinking ahead the Future of Additive Manufacturing – Innovation Roadmapping of Required Advancements" reveals the mandatory advancements required to qualify AM-technologies for DM. The study comprises a sophisticated overview on the overall proceeding in the project "Opportunities and Barriers of Direct Manufacturing Technologies", and outlines the main results in extracts. Comprehensive results are part of the confidential study that is accessible for DMRC partners.

Today's AM penetration is analyzed.

The presenty study firstly analyzes today's business of AM. Therefore, selected technologies are concisely described, and the current AM-penetration in the aerospace, automotive and electronics industry is examined.

The study develops future scenarios and discovers future applications.

Secondly, strategic product planning is carried out. The study describes the business of tomorrow by developing future scenarios for the aircraft and automotive production as well as for the electronics manufacturing equipment. Based on the future scenario and resulting future chances, risks and success factors, the study develops strategic directions for a successful penetration of AM in these three industries. Using these results as an impulse, ideas for future applications are discovered. These were pooled to innovation fields that were ranked according to their chances and risks.

The study deduces requirements on DM-technologies.

Requirements were validated; results are consolidated in innovation roadmaps.

Thirdly, as part of strategic technology planning required advancements of AM-technologies were deduced, means of requirements the identified applications impose on DM-technologies. The significance of these requirements was validated in a first expert survey. To promote the broad-scale implementation of AM, the technology development has to be aligned with the most significant future requirements, such as process stability, build-up rates, availability of new materials and material properties etc. As part of a second survey, for selected AM-technologies experts estimated the conceivable realization dates of the deduced requirements. The results were consolidated in innovation roadmaps. Accordingly, the technologies are expected to fulfill the majority of the listed requirements by 2020. Larger build chamber volumes, higher build-up rates and self-healing material properties are assessed to be met in the further future.

The project shows how to align technology development with future market needs.

All in all, the three study published during the project provide an overview of the procedure that allows transferring technological abilities into innovations. Reciprocally, it enables synchronizing the technology development (Technology Push) with the market requirements (Market Pull).

Auspicious applications should be pursued.

To optimally exploit the project's results and to enhance the penetration of AM in the three industries, particularly the most promising innovation fields should be addressed in the future. Therefore, realization and implementation studies have to be performed by industry experts in cooperation with AM-experts to prove the technical and economic feasibility. The development of the identified innovation fields as well as the emergence of further fields for the application of AM should be monitored continuously. In addition, innovation fields which offer great potential for the application of AM according to the experts' assessment, but entail great risks from today's point of view, should not be neglected.

The innovation roadmaps provide sophisticated decision maker information about when the identified applications can be realized. Concurrently, the roadmaps give hints on promising technology development paths and research directions. The gained results can be exploited for the development of future-oriented research strategies, as the process of aligning the technological development with the future market requirements is exactly the process to perform the transition of AM from an emerging to a (series) production-capable technology.

Outlook: Analysis of AM-research intensity and development of promising research strategies

To achieve this, the research work has to be bundled to consequently pursue research projects with maximum benefits for potential users of AM-technologies. This is the starting point for our next study conducted in close cooperation with the DMRC. The study analyzes the Additive Manufacturing Research Landscape and examines the (future) relevance of research. Based on this, the study deduces success factors for promising research strategies and reveals future-oriented research strategies. The public study comprising these results will be published in spring 2013.

Bibliography

[AFR10] Air Force Research Laboratory (Ed.): Shape Memory Polymer Materials Improve Composite Surface Antenna Reflectors. Materials & Manufacturing Directorate Wright-Patterson Air Force Base, Dayton, Ohio, 2010

[Alp13a-ol] Alpha Prototypes, Inc. (Ed.): FDM – Fused Deposition Modeling Under: http://www.alphaprototypes.com/FDM-Fused-Deposition-Modeling.aspx, Accessed in February 2013

[Alp13b-ol] Alpha Prototypes, Inc. (Ed.): Stereolithography. Under: http://www.alphaprototypes.com/stereolithography.aspx, Accessed in February 2013

[ASA11-ol] Aviation Supplier Web Log: Additive Manufacturing: A New Paradigm for Aircraft Parts. Under: http://aviationsuppliers.wordpress.com/2011/07/13/additive-manufacturing-a-new-paradigm-for-aircraft-parts/, Accessed in November 2011

[AST12] ASTM International (Ed.): Standard Terminology for Additive Manufacturing Technologies. Committee F42 on Additive Manufacturing, Subcommittee F42.91 on Terminology, West Conshohocken, United States, 2012

[Bar11] Baron, B.: Multifunctional Airframe Concepts with Structurally Integrated Electronics – Direct Part Manufacturing Workshop. Wright State University, March 2011

[Bas07-ol] BASF (Ed.): Newsletter – The Scales are Smiling. Under: http://www.plasticsportal.net/wa/plasticsEU~en_GB/portal/show/common/plasticsportal_news/2007/07_429, Accessed in January 2012

[BCC11-ol] BCC Research Market Forecasting: Global Electronics: High-Growth products and new markets. Under http://www.bccresearch.com/report/electronics-products-markets-ift063a.html, Accessed in November 2011

[BLR09] Bourell, D.; Leu, M.; Rosen, D.: Roadmap for Additive Manufacturing – Identifying the Future of Freeform Processing. The University of Texas, Austin, 2009

[BTW09] Blattmeier, M.; Töpker, J.; Witt, G.: Technologische Reife von generativen Herstellungsverfahren für Endanwendungen im Automobilbau. RTejournal, Aachen, 2009

[Bul09] Bullinger, H. (ed.): Technology Guide - Principles, Applications, Trends. Springer, Berlin, 2009

[CCD+11-ol] Campbell, I.; Combrink, J.; De Beer, D.; Barnard, L.: Stereolithography build time estimation based on volumetric calculations. Under: http://www.emeraldinsight.com/journals.htm?articleid=1747214&show=pdf, Accessed in February 2013

[CCY+11] Craeghs, T.; Clijsters, S.; Yasa, E.; Kruth, J.P.: Online quality control of selective laser melting. Department of Mechanical Engineering, Katholieke Universiteit Leuven, 2011

[Cev06] Cevolini, L.: Parts that go on the Final Car. International Conference on Future Industrial Applications of Additive Fabrication, 2006, Euromold 2006, Frankfurt

[Dil11-ol] Dillow, C.: Using 3-D Printing Tech, British Airbus Engineers Aim to Print Out an Entire Wing. Under: http://www.popsci.com/technology/article/2011-02/using-3-d-printing-tech-eads-wants-print-out-entire-aircraft-wing, Accessed in January 2012

[Dut10-ol] DUT Racing (Ed.): Additive Layer Manufacturing of Rear Engine Mount. Under: http://dutracing.nl/news/additive-layer-manufacturing-of-rear-engine-mount.html?lang=en, Accessed in January 2012

[Eco11-ol] The Economist Newspaper Limited (Ed.): The printed world. Under: http://www.economist.com/node/18114221?fsrc=rss&story_id=18114221, Accessed in November 2012

[Eco12] The Economist Newspaper Limited (Ed.): The third industrial revolution. Print edition, Apr 21st, London 2012

[EJN11-ol] Excell, J.; Nathan, S.: The rise of additive manufacturing. The Engineer. Under: http://www.theengineer.co.uk/in-depth/the-big-story/the-rise-of-additive-manufacturing/1002560.article, Accessed in November 2011

[Eos06-1-ol] EOS GmbH (Ed.): Gripper from automation engineering – Potential investigation with an innovative and award-winning result. Under: http://www.rm-platform.com/index.php?option=com_docman&task=doc_download&gid=425&Itemid=27, Accessed in December 2011

[Eos12-ol] EOS GmbH (Ed.): EOSINT P 395. Under: http://www.eos.info/fileadmin/user_upload/downloads_presse/pdf_files/EOS_Systemdatenblatt_P395_e_01.pdf, Accessed in February 2013

[Eos13a-ol] EOS GmbH (Ed.): Plastic Laser-Sintering Systems. Under: http://www.eos.info/en/products/systems-equipment/plastic-laser-sintering-systems.html, Accessed in February 2013

[Eos13b-ol] EOS GmbH (Ed.): e-Manufacturing Applications. Under: http://www.eos.info/en/applications.html, Accessed in February 2013

[Eos13c-ol] EOS GmbH (Ed.): EOSTATE 1.2. Under: http://www.eos.info/en/products/software.html, Accessed in February 2013

[Eos13d-ol] EOS GmbH (Ed.): Plastic Materials. Under: http://www.eos.info/en/products/materials/materials-for-plastic-systems.html, Accessed in February 2013

[Evo10-ol] Evonik Industries AG (Ed.): Elements 32 – Science Newsletter. Under: http://corporate.evonik.de/sites/dc/Downloadcenter/Evonik/Global/de/Magazine/elements/elements-32.pdf, Accessed in January 2012

[FCM+08] Fakhouri, V.; Cantale, N.; Mermoud, G.; Kim, J.; Boiko, D.; Charbon, E.; Martinoli, A.; Brugger, J.: Inkjet printing of SU-8 for polymer-based mems – A case study for microlenses. 2008 IEEE 21st International Conference on Micro Electro Mechanical Systems (MEMS), 13-17. Jan 2008, Tucson, 2008

[Fro07] Frost & Sullivan (Ed.): World Rapid Prototyping Equipment Markets, 2007

[GE11-ol] General Electric (Ed.): GE intensifies Focus on Additive Manufacturing. Under: http://www.genewscenter.com/content/detail.aspx?ReleaseID=12398&NewsAreaID=2, Accessed in November 2011

[Geb07] Gebhardt, A.: Generative Fertigungsverfahren. Rapid Prototyping – Rapid Tooling – Rapid Manufacturing. 3. Auflage, Hanser Verlag, München, 2007

[Geb12] Gebhardt, A.: Understanding Additive Manufacturing: Rapid Prototyping, Rapid Tooling, Rapid Manufacturing. Hanser Gardner Publications, Ohio, 2012

[GEK+11] Gausemeier, J.; Echterhoff, N.; Kokoschka, M.; Wall, M.: Thinking ahead the Future of Additive Manufacturing – Analysis of Promising Industries, University of Paderborn, 2011

[GEK+12] Gausemeier, J.; Echterhoff, N.; Kokoschka, M.; Wall, M.: Thinking ahead the Future of Additive Manufacturing – Future Applications, University of Paderborn, 2012

[GFB+11-ol] Gielies, T.; Fleurinck, M.; Bormans, J.; van Hooreweder, B.: Development of a Monoblock Titanium Steering Wheel for a Solar Powered Race Vehicle Using SLM. Under: http://www.fisita.com/education/congress/sc10/fisita2010scp34.pdf, Accessed in January 2012

[Gri03-ol] Grimm, T.: Fused deposition modeling: a technology evaluation. In: Time Compression, T.A. Grimm & Associates (Ed.), Volume 11, Issue 2, 2003

[GRS10] Gibson, I.; Rosen, D. W.; Stucker, B.: Additive Manufacturing Technologies – Rapid Prototying to Direct Digital Manufacturing. Springer Verlag, New York, Heidelberg, Dordrecht, London, 2010

[GPW09] Gausemeier, J.; Plass, C.; Wenzelmann, C.: Zukunftsorientierte Unternehmensgestaltung – Strategien, Geschäftsprozesse und IT-Systeme für die Produktion von morgen. Carl Hanser Verlag, München, Wien, 2009

[GPW13] Gausemeier, J.; Peter, S.; Wall, M.: Analysis of the Additive Manufacturing Research Landscape – Additive Manufacturing Research Map. Study for the Direct Manufacturing Research Center, Paderborn, to be published in March 2013

[HKF10] Haydock, H.; Kollamthodi, S.; Falconer, A.: EU Transport GHG: Routes to 2050 – Energy security and the transport sector. June 2010

[HP11-ol] Huffington Post: Can The Car Industry Lead the Jobs Recovery? Under: http://www.huffingtonpost.com/2011/08/02/auto-industry-jobs-recovery_n_916356.html, Accessed in November 2011

[Hyp11-ol] Hypersol: Research for the Benefit of SMEs. Research and development project funded by the European Union FP7 programme. Under: http://www.hypersol.info/aboutus.aspx, Accessed in November 2011

[Bro12-ol] Brooks, R.: Daimler Dives into Additive Manufacturing. In: IndustryWeek (Ed.). Under: http://www.industryweek.com/emerging-technologies/daimler-dives-additive-manufacturing, Accessed in November 2012

[KTL+09] KULKARNI, N. P.; TANDRA, G.; LIOU, F.W.; SPARKS, T.E.; RUAN, J.: Fuel Cell Development using additive manufacturing technologies – A review. Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, 2009

[Li01] LI, X.: Embedded sensors in layered manufacturing. Dissertation, Department of mechanical engineering, Stanford University, Stanford, California, 2001

[LL11-ol] LANGNAU, L.: Racing team to print 15 production parts for each car using additive manufacturing. Under: http://www.makepartsfast.com/2011/05/1885/racing-team-to-print-15-production-parts-for-each-car-using-additive-manufacturing/, Accessed in November 2011

[Mat11-ol] MATERIALISE (ED.): Materialise, DMEC and Kurimoto move additive manufacturing up a gear. Under: http://www.materialise.com/move-additive-manufacturing-up-gear, Accessed in November 2011

[May09-ol] MAYER, S.: Optimised mould temperature control procedure using DMLS. Under: http://www.eurekamagazine.co.uk/articles/18931/1054%20EOS%20Tooling%20Whitepaper.pdf, Accessed in January 2012

[Mor13-ol] MORRIS TECHNOLOGIES, INC. (ED.): DMLS Services: Additive Metal Manufacturing. Under: http://www.moristech.com/Aerospace/?cat=DMLS, Accessed in February 2013

[MTB+07] MAHESHWARAA, U.; TRADD, C.; BOURELL, D.; SEEPERSAD, C.C.: Design and Freeform Fabrication of Deployable Structures with Lattice Skins. Mechanical Engineering Department University of Texas at Austin, 2007

[Nat11-ol] NATHAN, S.: Composite Class: Developing the Airbus A350-XWB. Under: http://www.theengineer.co.uk/in-depth/the-big-story/composite-class-developing-the-airbus-a350-xwb/1009059.article, Accessed in January 2012

[NDS+04-ol] NORWOOD, A. J.; DICKENS, P. M.; SOAR, R.C.; HARRIS, R. A.; GIBBONS, G.; HANSELL, R.: Analysis of Cooling channels performance for cycle time reduction using rapid manufacturing techniques and computational fluid dynamic analysis. Under: https://dspace.lboro.ac.uk/dspace-jspui/bitstream/2134/4649/1/Norwood.pdf, Accessed in January 2012

[NMG+11-ol] NEUGEBAUER, R.; MÜLLER, B.; GEBAUER, M.; TÖPPEL, T.: Additive manufacturing boosts efficiency of heat transfer components. Under: http://www.emeraldinsight.com/journals.htm?issn=01445154&vol ume=31&issue=4&articleid=1953629&show=pdf, Accessed in January 2013

[Opt10-ol] OPTOMEC (ED.): Alternative Energy – Solar Cells. Under: http://www.optomec.com/Additive-Manufacturing-Applications/Printed-Electronics-for-Solar-Cells, Accessed in February 2013

[Par13-ol] PARAMOUNT INDUSTRIES (ED.): Stereolithography Rapid Prototypes. Under: http://www.paramountind.com/stereolithography.html, Accessed in February 2013

[PP11-ol] 3D PRO PARTS (ED.): Digital Manufacturing of Electrical Components. Under: http://www.3dproparts.com/sites/3dproparts.com/files/downloads/3dpp_electricalequip_dig_mfg.pdf, Accessed in November 2011

[PSS+07] PERIARD, D.; SCHAAL, N.; SCHAAL, M.; MALONE, E.; LIPSON, H.: Printing Food. Cornell University, Ithaca, 2007

[Pwc11-ol] PRICEWATERHOUSECOOPERS (ED.): Aerospace & Defence – 2010 year in review and 2011 forecast. Under: http://www.pwc.de/de_DE/de/industrielle-produktion/assets/A_D_2010_review_and_2011_forecast.pdf, Accessed in January 2012

[RE11] RANGE, G. P.; EL-TAHCH, A.: Aerospace Industry Overview and Update, 2011

[Rea11-ol] REALIZER GMBH (ED.): Selective Laser Melting – Visions become Reality. Under: http://www.realizer.com/startseite/downloads, November 2012

[REC11-ol] ROYAL ENGINEERING COMPOSITES (ED.): Engine Components. Under: http://www.royalcomposites.com/products/engine-components, Accessed in November 2011

[Red11-ol] REDAHAN, E.: Innovation in automation. Under: http://www.iom3.org/news/innovation-automation-robots-shrewbot, Accessed in January 2012

[Ree09] REEVES, P.: Additive Value – Phil Reeves, Managing Director of Econolyst, reviews the 4th International Additive Manufacturing Conference, MWP, Centaur Communications, p.44-45, London, September 2009

[Ren13-ol] RENISHAW (ED.): Laser melting applications. Under: http://www.renishaw.com/en/laser-melting-applications--15256, Accessed in February 2013

[Rij11] DE RIJCK, S.: Productgrenzen verleggen met additive manufacturing. Presentation Materialise Group, 2011

[SA10] Sridhar, A.; Attanasio, D.: Trends and Expertise Exchange within Rapid Manufacturing in Europe. Forum for Rapid Technology, Edition 7 (2010), RTejournal, 2010

[Sch11-ol] Schlieper, G.: Designing complex structures using Selective Laser Sintering (SLS). 2010 Hagen Symposium Reports. Under: http://www.ipmd.net/news/001071.html, Accessed in January 2012

[Sci11-ol] Science Daily (Ed.): Engineers Look to the Birds for the Future of Unmanned Aerial Vehicles. Under: http://www.sciencedaily.com/releases/2011/06/110607121148.htm, Accessed in February 2012

[Slm13a-ol] SLM SOLUTIONS GMBH (Ed.): Laser Beam Melting System SLM® 250 HL. Under: http://www.slm solutions.com/cms/upload/pdf/120923_SLM_250_Flyer.pdf, Accessed in February 2013

[Slm13b-ol] SLM SOLUTIONS GMBH (Ed.): Do you know everything about SLM®? Under: http://www.slm-solutions.com/cms/upload/pdf/121004_SLM_Gesamt.pdf, Accessed in February 2013

[Slm13c-ol] SLM SOLUTIONS GMBH (Ed.): Discover the variety. Under: http://www.slm-solutions.com/cms/upload/pdf/120923_SLM_Materialien.pdf, Accessed in February 2013

[Slm13d-ol] SLM SOLUTIONS GMBH (Ed.): Business Fields. Under: http://www.slm-solutions.com/en/business-fields/automotive/, Accessed in February 2013

[SI10-ol] Starr, S.; IPC – Association Connecting Electronics Industries Inc. (Ed.): Report on Phase I of IPC Market Research on Electronics Technology Trends: Insights about 10 Key Trends from Interviews with Industry Experts. Under: http://www.fed.de/downloads/TECHTR-10WP.pdf, Accessed in February 2013

[Str09a-ol] Stratasys, Inc. (Ed.): FORTUS 360mc/400mc Accuracy Study. Under: http://www.fortus.com/Products/~/media/Fortus/Files/PDFs/WP-Fortus400mcAccuracyStudy.ashx, Accessed in February 2013

[Str09b-ol] Stratasys, Inc. (Ed.): Direct Digital Manufacturing at BMW. Under: http://www.stratasys.com/~/media/Main/Files/Case%20Studies/Automotive/APBMWAutomotiveMfgToolsDDM.ashx, Accessed in February 2013

[Str11a-ol] Stratasys, Inc. (Ed.): An eye for direct digital manufacturing. Under: http://www.stratasys.com/~/media/Main/Files/Case%20Studies/Aerospace/AP-DSTAerospace-EndUseParts-DDM.ashx, Accessed in November 2012

[Str11b-ol] Stratasys, Inc. (Ed.): Manufacturing Jigs and Fixtures with FDM. Under: http://www.stratasys.com/Resources/Case-Studies/Automotive-FDM-Technology-Case-Studies/BMW-Manufacturing-Tools.aspx, Accessed in November 2012

[Str11c-ol] Stratasys, Inc. (Ed.): ABSplus-P430 for Fortus 3D Production Systems. Under: http://www.fortus.com/Products/~/media/41E2E4486D5F4BCB8B530B8790484542.ashx, Accessed in February 2013

[Str12a-ol] Stratasys, Inc. (Ed.): Solutions – Industries – Automotive.Under: http://www.stratasys.com/Solutions/Industries/Automotive.aspx, Accessed in February 2013

[Str12b-ol] Stratasys, Inc. (Ed.): 3D Printing is Merged with Printed Electronics. Under: http://investors.stratasys.com/releasedetail.cfm?ReleaseID=659142, Accessed in November 2012

[Str13a-ol] Stratasys, Inc. (Ed.): Industries Using FDM Technology. Under: http://www.stratasys.com/Solutions/Industries.aspx, Accessed in February 2013

[Str13b-ol] Stratasys, Inc. (Ed.): Technology: Fused Deposition Modeling. Under: http://www.stratasys.com/Solutions/Technology.aspx, Accessed in February 2013

[SZW11-ol] SZ&W Group (Ed.): Automotive. Under: http://www.szwgroup.com/ind_aut.asp, Accessed in November 2011

[TCT10-ol] TCT Magazine online (Ed.): Within Technologies and 3T RPD Herald a new era in design. Newsletter, issue 18/4, 2010. Under: http://www.tctmagazine.com/img/static/TCT18_4p9LR.pdf, Accessed in February 2012

[Thr12-ol] Thryft, A.R.: 3D Printing Flies High. In: Design News, UBM Electronics (Ed.)Under: http://www.designnews.com/author.asp?doc_id=251526&section_id=1392&dfpPParams=ind_183,industry_auto,industry_aero,bid_27,aid_251526&dfpLayout=blog, Accessed in November 2012

[TMW11-ol] Today's machining world (Ed.): Stratasys leads Additive Manufacturing Industry for Ninth Consecutive Year. Under: http://www.todaysmachiningworld.com/stratasys-leads-additive-manufacturing-industry-for-ninth-consecutive-year/, Accessed in November 2011

[Wei06-ol] WEISSHAAR, T. A.: Morphing Aircraft Technology – New Shapes for Aircraft Design. Aeronautics and Astronautics Department Purdue University, 2006. Under: http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA479821, Accessed in December 2011

[Woh11] WOHLERS, T.: Wohlers Report 2011 – Additive Manufacturing and 3D Printing State of the Industry. Wohlers Associates Inc., United States of America, 2011

[Woh12] WOHLERS, T.: Wohlers Report 2012 – Additive Manufacturing and 3D Printing State of the Industry. Wohlers Associates Inc., United States of America, 2012

[Woo12-ol] WOOLLACOTT, E.; : 3D printing of personal electronics. In: TG Daily, DD&M,Inc. (Ed.). Under: http://www.tgdaily.com/hardware-features/67646-3d-printing-of-personal-electronics, Accessed in November 2012

[Wor10] WORKSHOP: Opportunities and Barriers of DM Technologies within the Aerospace Industry and adapted others. Heinz Nixdorf Institute, Paderborn, October 2010

[Wor11a] WORKSHOP: Idea Creation for DM-Applications in the Aerospace Industry. The Boeing Comapny, St. Louis, MO, May 2011

[Wor11b] WORKSHOP: Idea Creation for DM-Applications in the Automotive Industry. Heinz Nixdorf Institute, Paderborn, March 2011

[Wor11c] WORKSHOP: Idea Creation for DM-Applications in the Electronics Industry. Heinz Nixdorf Institute, Paderborn, June 2011

[WW10-ol] WEGNER, A.; WITT, G.: Additive manufacturing of parts with integrated functions. Under: http://www.thefreelibrary.com/Additive+manufacturing+of+parts+with+integrated+functions.-a0246014047, Accessed in January 2012

[YRV+07] YANG, L., RIDA, A., VYAS, R., TENTZERIS, M. M.: RFID tag and RF structures on a paper substrate using inkjet printing technology. IEEE transactions on Microwave Theory and Techniques, Vol. 55, No. 12, December 2007

[Zul11-ol] ZULFIKLI, S. A.: Energy recovery from landing aircraft. Under: http://www.megs.ac.uk/megs/images-multimedia/documents/shamsulaizam.pdf, Accessed in January 2012

[3ds13a-ol] 3D SYSTEMS CORPORATION (ED.): Stereolithography (SLA®). What is Stereolithography? Under: http://production3dprinters.com/sla/stereolithography, Accessed in February 2013

[3ds13b-ol] 3D SYSTEMS CORPORATION (ED.): Accura® Stereolithography (SLA) Materials. Under: http://production3dprinters.com/materials/sla, Accessed in February 2013

[3ds13c-ol] 3D SYSTEMS CORPORATION (ED.): SLA ® System Software. Under: http://production3dprinters.com/support/software/sla, Accessed in February 2013

[3ds13d-ol] 3D SYSTEMS CORPORATION (ED.): Production Printing Success Stories. Under: http://production3dprinters.com/resources/success-stories?tid=16&tid_1=All, Accessed in February 2013

A1

Expert Survey on Current and Future Requirements on Direct Manufacturing Technologies

Expert survey on current and future requirements on Direct Manufacturing technologies

The Direct Manufacturing Research Center (DMRC) has the goal to advance Additive Manufacturing (AM)-technologies from Rapid Prototyping technologies to dependable Direct Manufacturing (DM)-technologies. Therefore, it is necessary to align the technology development with current and future requirements on DM-technologies. In collaboration with the DMRC, the Heinz Nixdorf Institute is conducting an expert survey to identify the most important requirements.

We highly appreciate your feedback concerning 7 general requirements and 19 technology-specific requirements on DM-technologies. Therefore, we first ask you to assess the **significance** of the selected requirements for the DM-industry. Secondly, we would like you to judge on how well the listed companies or technologies perform with regard to these requirements (**degree of performance**).

The information you provide within this survey will be evaluated for scientific purposes and will be treated as confidential. We explicitly declare that we will neither publish nor make otherwise available your personal data to any third party. The completion of this survey will approximately take 30 minutes. Your feedback is very important for us. After the evaluation of the survey, you will get an electronic version of the results. In addition we will provide you the study including the results of the survey exclusively and free of charge. Thank you for your support.

Contact
After completing this survey, please safe your information and send the file by email to Niklas Echterhoff or Marina Wall, Heinz Nixdorf Institute, E-mail: Niklas.Echterhoff@hni.uni-paderborn.de / Marina.Wall@hni.uni-paderborn.de. If you prefer conventional mail, please send your print to Heinz Nixdorf Institute, Niklas Echterhoff, Fuerstenallee 11, 33102 Paderborn, Germany. In case of any questions, please do not hesitate to ask. Our phone number: +49-5251-606264 / +49-5251-606496.

Personal Information

Name:	Company:
E-Mail:	Date:

DMRC
DIRECT MANUFACTURING RESEARCH CENTER

HEINZ NIXDORF INSTITUTE
University of Paderborn
Product Engineering
Prof. Dr.-Ing. Jürgen Gausemeier

Part 1: General Information

Please give us some general information about your professional background.

1. *In which part of the value chain of Additive Manufacturing are you working?*
   - ❑ Machine Manufacturer
   - ❑ Material Supplier
   - ❑ User
   - ❑ University / Research Facility
   - ❑ Consulting
   - ❑ ________________________

2. *If you are a user of AM-technologies, how do you use them?*
   - ❑ Rapid Prototyping
   - ❑ Rapid Tooling
   - ❑ Direct Manufacturing
   - ❑ ________________________

3. *In which company division are you working?*
   - ❑ Research & Development
   - ❑ Modeling / Prototyping
   - ❑ Production
   - ❑ Sales
   - ❑ Quality Assurance
   - ❑ Maintenance and Repair
   - ❑ Purchase
   - ❑ Marketing
   - ❑ Management
   - ❑ _________________________

4. *What is your Job Title?*

   _______________________________________ (i.e.: CEO, VP Technical Operations etc.)

5. *In which area are you expert?*
   - ❑ Technology
   - ❑ Market and Competition

6. *Number of employees in 2010*

Company	……………… employees
Field of Additive Manufacturing	……………… employees

For questions please contact: Mr. Niklas Echterhoff / Mrs. Marina Wall, Heinz Nixdorf Institute
(E-Mail: Niklas.Echterhoff@hni.upb.de / Marina.Wall@hni.upb.de, Phone: +49-5251-606264 /+49-5251-606496)

7. *Revenue in 2010 [in Mio. EUR]*

Company						
	< 5	5 - 10	11 - 20	21 - 50	51 - 100	> 100
	❑	❑	❑	❑	❑	❑
Field of Additive Manufacturing						
	< 1	1 - 5	6 - 10	11 - 20	21 - 50	> 50
	❑	❑	❑	❑	❑	❑

8. *Development of revenues [annual growth rate in %, the average of the last three years]*

Company						
	< 0	0 - 2	3 - 5	6 - 10	11 - 20	> 20
	❑	❑	❑	❑	❑	❑
Field of Additive Manufacturing						
	< 0	0 - 2	3 - 5	6 - 10	11 - 20	> 20
	❑	❑	❑	❑	❑	❑

9. *Field of research and action within Additive Manufacturing*

   Please name fields of research or action that are of great importance for you within the context of Additive Manufacturing.

For questions please contact: Mr. Niklas Echterhoff / Mrs. Marina Wall, Heinz Nixdorf Institute
(E-Mail: Niklas.Echterhoff@hni.upb.de / Marina.Wall@hni.upb.de, Phone: +49-5251-606264 /+49-5251-606496)

Part 2: General Requirements

In the following you find 7 general requirements. Please specify the significance of each requirement for the DM-industry from today's point of view and its significance in 2020, differentiating the significance for machine manufacturers (MM) and material suppliers (MS) on a scale from "0" to "4" (no significance up to high significance). Then please estimate each company's degree of performance regarding each requirement. Please use the given scale from "0" (i.e. you think there is a call for action for the company) to "4" (i.e. the company has got a distinctive strength concerning this requirement).

You can either evaluate all of the listed companies or selected ones. Please make sure to evaluate as many of the listed companies as possible. If you see further general requirements, please add and assess them below.

Example:

	Significance				Degree of Performance
	MM		MS		Company 1
	Today	2020	Today	2020	
High innovation ability	2	4	1	4	2

Today, a high innovation ability has got a medium significance for the DM-industry from your point of view. Until 2020, the significance will immensely increase. But the company's performance is unsatisfying regarding this requirement.

	Significance				Degree of performance				
	MM		MS		3D Systems	EOS	Evonik	SLM	Stratasys
	Today	2020	Today	2020					
1) High innovation ability									
2) Strong competences to provide solutions									
3) Strong consulting competences (pre-sales support)									
4) Strong competences for maintenance and support (post-sales / application support)									
5) Distinct customer orientation									
6) Provision of qualification courses for users									
7) Continuous IT support from CAD-file creation to part measurement									
8)									
9)									
10)									

For questions please contact: Mr. Niklas Echterhoff / Mrs. Marina Wall, Heinz Nixdorf Institute
(E-Mail: Niklas.Echterhoff@hni.upb.de / Marina.Wall@hni.upb.de, Phone: +49-5251-606264 /+49-5251-606496)

Part 3: Technology-specific Requirements

In the following you find 19 technology-specific requirements. Please specify the significance of each requirement for the DM-industry from today's point of view and its significance in 2020 on a scale from "0" to "4" (no significance up to high significance). Then please estimate each technology's performance regarding each requirement. Please use the given scale from "0" (i.e. you think there is a call for action) to "4" (i.e. the technology has got a distinctive strength concerning this requirement).

You can either evaluate all of the listed technologies or selected ones. Please make sure to evaluate as many of the listed technologies as possible. Within the free columns you can add and assess further technologies.

Example:

	Significance		Degree of Performance
	Today	2020	Technology 1
Build chamber volume > 8 m^3	2	4	1

Today, the build chamber volume of 8 m^3 has got a medium significance for the DM-industry from your point of view. Until 2020, the significance will immensely increase. But the technology's performance is unsatisfying regarding this requirement.

	Significance		Degree of performance					
	Today	2020	Powder bed fusion – Plastic (e.g. SLS)	Powder bed fusion – Metal (e.g. SLM)	Fused Layer Modeling (e.g. FDM)	Polymerisation (e.g. Stereolitho-graphy)		
1) Build chamber volume (V in m^3)								
a) $V < 1\ m^3$								
b) $1\ m^3 \leq V \leq 8\ m^3$								
c) $V > 8\ m^3$								
2) Build-up rates (production speed at highest quality in cm^3/h)								
a) 1 - 10 cm^3/h								
b) 11 - 40 cm^3/h								
c) 41 - 100 cm^3/h								
d) > 100 cm^3/h								
3) Minimal surface quality of parts with highest quality (measured by its average surface finish R_a)								
a) $R_a > 10$ µm								
b) 5 µm $\leq R_a \leq$ 10 µm								
c) 1 µm $\leq R_a <$ 5 µm								
d) $R_a < 1$ µm								
4) Dimensional accuracy (average deviation in µm)								
a) < ± 50 µm								
b) ± 50 - 100 µm								
c) > ± 100 µm								

For questions please contact: Mr. Niklas Echterhoff / Mrs. Marina Wall, Heinz Nixdorf Institute
(E-Mail: Niklas.Echterhoff@hni.upb.de / Marina.Wall@hni.upb.de, Phone: +49-5251-606264 /+49-5251-606496)

	Significance		Degree of performance					
	Today	2020	Powder bed fusion – Plastic (e.g. SLS)	Powder bed fusion – Metal (e.g. SLM)	Fused Layer Modeling (e.g. FDM)	Polymerisation (e.g. Stereolitho-graphy)		
5) Layer thickness (in mm)								
a) < 0,05 mm								
b) 0,05 - 0,099 mm								
c) 0,1 mm - 2 mm								
6) Machine incidental acquisition costs (in % p.a. referring to machine acquisition costs)								
a) < 5% p.a.								
b) 5 - 10% p.a.								
c) 11 - 15% p.a.								
d) > 15% p.a.								
7) Maintenance costs (in % p.a. referring to machine acquisition costs)								
a) < 10% p.a.								
b) 10% - 20% p.a.								
c) > 20% p.a.								
8) Processability of materials with AM-machines								
a) Magnesium								
b) Carbon-fiber-reinforced polymer(CFRP)								
c) Liquid crystalline polymers (LCP)								
d) Shape memory alloys (SMA)								
e)___________________								
9) Availability of new material properties								
a) Fire resistance								
b) Thermal conductivity								
c) Electrical conductivity								
d) Self-healing properties								
10) Flexible / hybrid material processing								
a) Processing different types of material by one machine (sequential processing of e.g. plastics and metals)								
b) Processing different types of material within one job (simultaneous multimaterial processing of e.g. plastics and metals)								
11) Possibility to build up on existing structures								
a) Building up on flat surface								
b) Building up on 3-D surface								

For questions please contact: Mr. Niklas Echterhoff / Mrs. Marina Wall, Heinz Nixdorf Institute
(E-Mail: Niklas.Echterhoff@hni.upb.de / Marina.Wall@hni.upb.de, Phone: +49-5251-606264 /+49-5251-606496)

	Significance		Degree of performance					
	Today	2020	Powder bed fusion – Plastic (e.g. SLS)	Powder bed fusion – Metal (e.g. SLM)	Fused Layer Modeling (e.g. FDM)	Polymerisation (e.g. Stereolitho-graphy)		
12) Quality control in production processes								
a) Conduct quality control after job completion								
b) Conduct quality control on-line (during the job)								
13) Process integration								
a) Partial integration (e.g. powder management system)								
b) Automated integration of AM-machines into production line								
c) Highly integrated AM-machine (machine as production line)								
14) Certification								
a) Ensure continuous certification in the aircraft production (usability of parts in aviation)								
b) Ensure continuous certification in the automotive production (usability of parts in traffic)								
c) Ensure continuous certification in the manufacturing equipment (usability of parts in manufacturing equipment)								
15) High process stability								
16) Integration of electronic circuits into additively manufactured parts								
17) Provision of design rules								
18) Availability of a database containing properties of additively processed materials (e.g. thermal characteristics, tensile strength etc.)								
19) Recyclability of materials								

If you see further technology-specific requirements, please add and assess them on page 8.

For questions please contact: Mr. Niklas Echterhoff / Mrs. Marina Wall, Heinz Nixdorf Institute
(E-Mail: Niklas.Echterhoff@hni.upb.de / Marina.Wall@hni.upb.de, Phone: +49-5251-606264 /+49-5251-606496)

Part 4: Final Statement

Are there further aspects we have not considered yet? Please notice them below.

Thank you for taking part in this expert survey.

For questions please contact: Mr. Niklas Echterhoff / Mrs. Marina Wall, Heinz Nixdorf Institute
(E-Mail: Niklas.Echterhoff@hni.upb.de / Marina.Wall@hni.upb.de, Phone: +49-5251-606264 /+49-5251-606496)

A2

Expert Survey on Advancements of Direct Manufacturing Technologies

Expert survey on advancements of Direct Manufacturing technologies

The Direct Manufacturing Research Center (DMRC) has the goal to advance Additive Manufacturing (AM)-technologies from Rapid Prototyping to dependable Direct Manufacturing (DM)-technologies. To achieve this, it is necessary to align the technology development with current and future requirements on Direct Manufacturing. In the project "Opportunities and Barriers of Direct Manufacturing Technologies", conducted by the DMRC and the Heinz Nixdorf Institute, we identified (future) promising applications for Direct Manufacturing. Based in this, required advancements of AM-technologies – in terms of requirements each application imposes on DM-technologies – were deduced and validated in an expert survey.

In the present survey, we highly appreciate your feedback concerning 16 requirements. Therefore, we ask you to estimate the **point in time** when – from you point of view – the selected requirements will be fulfilled by selected AM-technologies. This will allow creating innovation roadmaps, indicating when the identified future applications can be manufactured as technological requirements will be fulfilled.

The information you provide within this survey will be evaluated for scientific purposes and will be treated as confidential. We explicitly declare that we will neither publish nor make otherwise available your personal data to any third party. The completion of this survey will approximately take 30 minutes. Your feedback is very important for us. After the evaluation of the survey, you will get an electronic version of the results. In addition we will provide you the study including the results of the survey exclusively and free of charge. Thank you for your support.

Contact
After completing this survey, please save your information and send the file by email to Marina Wall or Niklas Echterhoff, Heinz Nixdorf Institute, Email: Marina.Wall@hni.uni-paderborn.de / Niklas.Echterhoff@hni.uni-paderborn.de. If you prefer conventional mail, please send your print to Heinz Nixdorf Institute, Marina Wall, Fuerstenallee 11, 33102 Paderborn, Germany. In case of any questions, please do not hesitate to ask. Our phone number: +49-5251-606496 / +49-5251-606264.

Personal Information

Name:	Company:
E-Mail:	Date:

DMRC
DIRECT MANUFACTURING RESEARCH CENTER

HEINZ NIXDORF INSTITUTE
University of Paderborn
Product Engineering
Prof. Dr.-Ing. Jürgen Gausemeier

Expert survey on advancements of Direct Manufacturing technologies Page 2 of 6

Part 1: General Information

Please give us some general information about your professional background.

1. *In which part of the value chain of Additive Manufacturing are you working?*

- ❑ Machine Manufacturer
- ❑ Material Supplier
- ❑ User
- ❑ University / Research Facility
- ❑ Consulting
- ❑ ________________________

2. *If you are a user of AM-technologies, how do you use them?*

- ❑ Rapid Prototyping
- ❑ Rapid Tooling
- ❑ Direct Manufacturing
- ❑ ________________________

3. *In which company division are you working?*

- ❑ Research & Development
- ❑ Modeling / Prototyping
- ❑ Production
- ❑ Sales
- ❑ Quality Assurance
- ❑ Maintenance and Repair
- ❑ Purchase
- ❑ Marketing
- ❑ Management
- ❑ _________________________

4. *In which area are you expert?*

- ❑ Technology
- ❑ Market and Competition

5. *Field of research and action within Additive Manufacturing*

Please name fields of research or action that are of great importance for you within the context of Additive Manufacturing.

____

____

____

____

____

____

____

For questions please contact: Mrs. Marina Wall / Mr. Niklas Echterhoff, Heinz Nixdorf Institute
(E-Mail: Marina.Wall@hni.upb.de / Niklas.Echterhoff@hni.upb.de, Phone: +49-5251-606496/+49-5251-606264)

Part 2: Technology-Specific Requirements

In the following, you find 16 technology-specific requirements. Please estimate the point in time when – from your point of you – the listed requirements will be fulfilled by each technology. Therefore, you will only have to choose between one of the five available points in time for each requirement and each technology.

You can either evaluate all of the listed technologies or selected ones. Please make sure to evaluate as many technologies as possible.

Example:

	Powder bed fusion – Plastic (e.g. SLS)				
	2012 – 2013	2014 – 2016	2017 – 2020	2021 – 2025	2026 – 2030
Build chamber volume> 8 m^3	☐	☐	☐	☒	☐

From your point of view, a build chamber volume of more than 8 m^3 will be available for powder bed fusion plastic technologies from 2021 onwards.

	Powder bed fusion – Plastic (e.g. SLS)					***Powder bed fusion – Metal (e.g. SLM)***					***Fused Layer Modeling (e.g. FDM)***					***Polymerization (e.g. Stereolithography)***				
	2012 – 2013	2014 – 2016	2017 – 2020	2021 – 2025	2026 – 2030	2012 – 2013	2014 – 2016	2017 – 2020	2021 – 2025	2026 – 2030	2012 – 2013	2014 – 2016	2017 – 2020	2021 – 2025	2026 – 2030	2012 – 2013	2014 – 2016	2017 – 2020	2021 – 2025	2026 – 2030
1) Build chamber volume (V in m^3)																				
a) $1\ m^3 \leq V \leq 2\ m^3$																				
b) $2\ m^3 < V \leq 8\ m^3$																				
c) $V > 8\ m^3$																				
2) Build-up rates (B) (production speed at highest quality in cm^3/h)																				
a) $80\ cm^3/h \leq B \leq 120\ cm^3/h$																				
b) $120\ cm^3/h < B \leq 150\ cm^3/h$																				
c) $B > 150\ cm^3/h$																				

For questions please contact: Mrs. Marina Wall / Mr. Niklas Echterhoff, Heinz Nixdorf Institute
(E-Mail: Marina.Wall@hni.upb.de / Niklas.Echterhoff@hni.upb.de, Phone: +49-5251-606496/+49-5251-606264)

	Powder bed fusion – Plastic (e.g. SLS)					*Powder bed fusion – Metal (e.g. SLM)*					*Fused Layer Modeling (e.g. FDM)*					*Polymerization (e.g. Stereolithography)*				
	2012 – 2013	2014 – 2016	2017 – 2020	2021 – 2025	2026 – 2030	2012 – 2013	2014 – 2016	2017 – 2020	2021 – 2025	2026 – 2030	2012 – 2013	2014 – 2016	2017 – 2020	2021 – 2025	2026 – 2030	2012 – 2013	2014 – 2016	2017 – 2020	2021 – 2025	2026 – 2030
3) High process stability (deviation (D) of reproducibility in case of identical process chain)																				
a) 0.1 % ≤ D ≤ 0.5 %																				
b) D < 0.1 %																				
4) Integration of electronic circuits																				
5) Dimensional accuracy (average deviation in µm)																				
a) < ± 25 µm																				
b) ± 25-50 µm																				
6) Flexible / hybrid material processing																				
a) Sequential processing of different material types by one machine (e.g. plastics and metals)																				
b) Simultaneous processing of different material types within one job (e.g. plastics and metals)																				
7) Possibility to build up on existing 3-D surface structures																				
8) Conduct quality control of the raw material during production (e.g. powder quality)																				
9) Quality control in production processes																				
a) Conduct quality control after job completion																				
b) Conduct quality control on-line (during the job)																				
10) Process integration																				
a) Partial integration (powder management system)																				
b) Automated integration of AM-machines																				
c) Highly integrated AM-machine																				

For questions please contact: Mrs. Marina Wall / Mr. Niklas Echterhoff, Heinz Nixdorf Institute
(E-Mail: Marina.Wall@hni.upb.de / Niklas.Echterhoff@hni.upb.de, Phone: +49-5251-606496/+49-5251-606264)

	Powder bed fusion – Plastic (e.g. SLS)					*Powder bed fusion – Metal (e.g. SLM)*					*Fused Layer Modeling (e.g. FDM)*					*Polymerization (e.g. Stereolithography)*				
	2012 – 2013	2014 – 2016	2017 – 2020	2021 – 2025	2026 – 2030	2012 – 2013	2014 – 2016	2017 – 2020	2021 – 2025	2026 – 2030	2012 – 2013	2014 – 2016	2017 – 2020	2021 – 2025	2026 – 2030	2012 – 2013	2014 – 2016	2017 – 2020	2021 – 2025	2026 – 2030
11) Certification																				
a) Continuous certification in aircraft production																				
b) Continuous certification in automotive production																				
c) Continuous certification in manufacturing equipment																				
12) Processability of materials with AM-machines																				
a) Magnesium																				
b) Carbon-fiber-reinforced polymer(CFRP)																				
c) Liquid crystalline polymers (LCP)																				
d) Shape memory alloys (SMA)																				
e) Ceramic																				
13) Availability of new material properties																				
a) Fire resistance																				
b) Thermal conductivity																				
c) Electrical conductivity																				
d) Self-healing properties																				
14) Recyclability of materials																				
15) Material certification																				
16) Availability of design rules																				
17) Availability of a database containing properties of AM-materials (e.g. thermal characteristics etc.)																				

For questions please contact: Mrs. Marina Wall / Mr. Niklas Echterhoff, Heinz Nixdorf Institute
(E-Mail: Marina.Wall@hni.upb.de / Niklas.Echterhoff@hni.upb.de, Phone: +49-5251-606496/+49-5251-606264)

Part 3: Final Statement

Are there further aspects we have not considered yet? Please notice them below.

Thank you for taking part in this expert survey.

For questions please contact: Mrs. Marina Wall / Mr. Niklas Echterhoff, Heinz Nixdorf Institute
(E-Mail: Marina.Wall@hni.upb.de / Niklas.Echterhoff@hni.upb.de, Phone: +49-5251-606496/+49-5251-606264)

Picture Credits

Figure 1-9, page 23: Pictures courtesy of: © Morris Technologies Inc., © Morris Technologies Inc. – Swirler fuel injection nozzle for gas turbine applications, © Rainer Plendl (Fotolia), © EOS GmbH, © Kor Ecologic Inc. – The Urbee Hybrid, © Nervous System – Twist Ring produced by Cookson Precious Metals Digital Forming, © Digital – Forming Cufflinks produced by Cookson Precious Metals, © SLM Solutions GmbH – Hip implant made of Ti6Al4V, © DePuy – Expedium SFX Cross Connector measuring device, © Freedom of Creation – Laser Sintered dress designed by Jane Kyttanen and Jiri Evenhuis, © Lionel T Dean, FutureFactories, © DEKA – Humeral mount for a fully integrated prosthetic arm made of Ti64 by EOS GmbH, © Windell H. Oskay, Evil Mad Science LLC (www.evilmadscientist.com), © Stratasys Inc., © Maridav (Fotolia), © Rainer Plendl (Fotolia)

Figure 2-1, page 33:: Pictures courtesy of Fotolia: © Bernd Kröger, © eyewave, © N-Media-Images, © Eisenhans, © Franz Pfluegl, © johas, © Henry Schmitt, © Kurhan, © Rainer Plendl, © Tanja Bugussat, © fazon, © braverabbit, © Sergej Khackimullin, © Photokreatief, © pink candy, © dieter76, © Marc Heiligenstein, © PictureArt, © KaYann, © Alain Lavanchy, © Thaut Images, © Beboy, © Paul Fleet, © apfelweile, © Thomas Müller

Figure 2-2, page 35: Pictures courtesy of Fotolia: © Acies, © mark yuill, © Scanrail, © RRF, © Xaver Klaußner, © corepics, © Vladimir Vydrin, © Jeanette Dietl, © LobsteR, © Alexander Raths, © Thomas Sztanek, © T. Michel, © FotoEdhar, © Coka, © Michael Nivelet. Pictures courtesy of: © The Boeing Company (BoeingImages.de): BBJ Winglet, Fuselage and Left Engine, Composite Materials Fabrication, BBJ Passenger Cabin, Dreamliner Lighting Concept; © Stratasys Inc., © ISO/IEC, © ASTM, © DIN Deutsches Institut für Normung e. V.

Figure 2-3, page 36: Pictures courtesy of Fotolia: © Maksim Toome, © Gary, © ag visuell, © Kayros Studio, © Jürgen Effner, © Rainer Plendl, © Nneirda, © Stefan Körber, © cyrano, © Oleksander Moroz, © Elenathewise, © imageteam, © Vladimir Melnik, © Benjamin Thorn, © Alexander Mitiuic, © andrea lehmkuhl, © Anton Balazh, © cpauschert, © skvoor; © ISO/IEC, © ASTM, © DIN Deutsches Institut für Normung e. V.

Figure 2-4, page 38: Pictures courtesy of Fotolia: © TrudiDesign, © Rainer Plendl, © Stauke, © Nmedia, © yang yu, © octus, © Alexander Raths, © higyou, © LE image, © Izaokas Sapiro, © Cybrain, © annadrozd, © Dimitry Kolmakov, © S!mon; Pictures courtesy of: © Stratasys Inc.; © ISO/IEC, © ASTM, © DIN Deutsches Institut für Normung e. V.

Figure 2-12, page 50: Google 3D-Gallery: © ilotopi