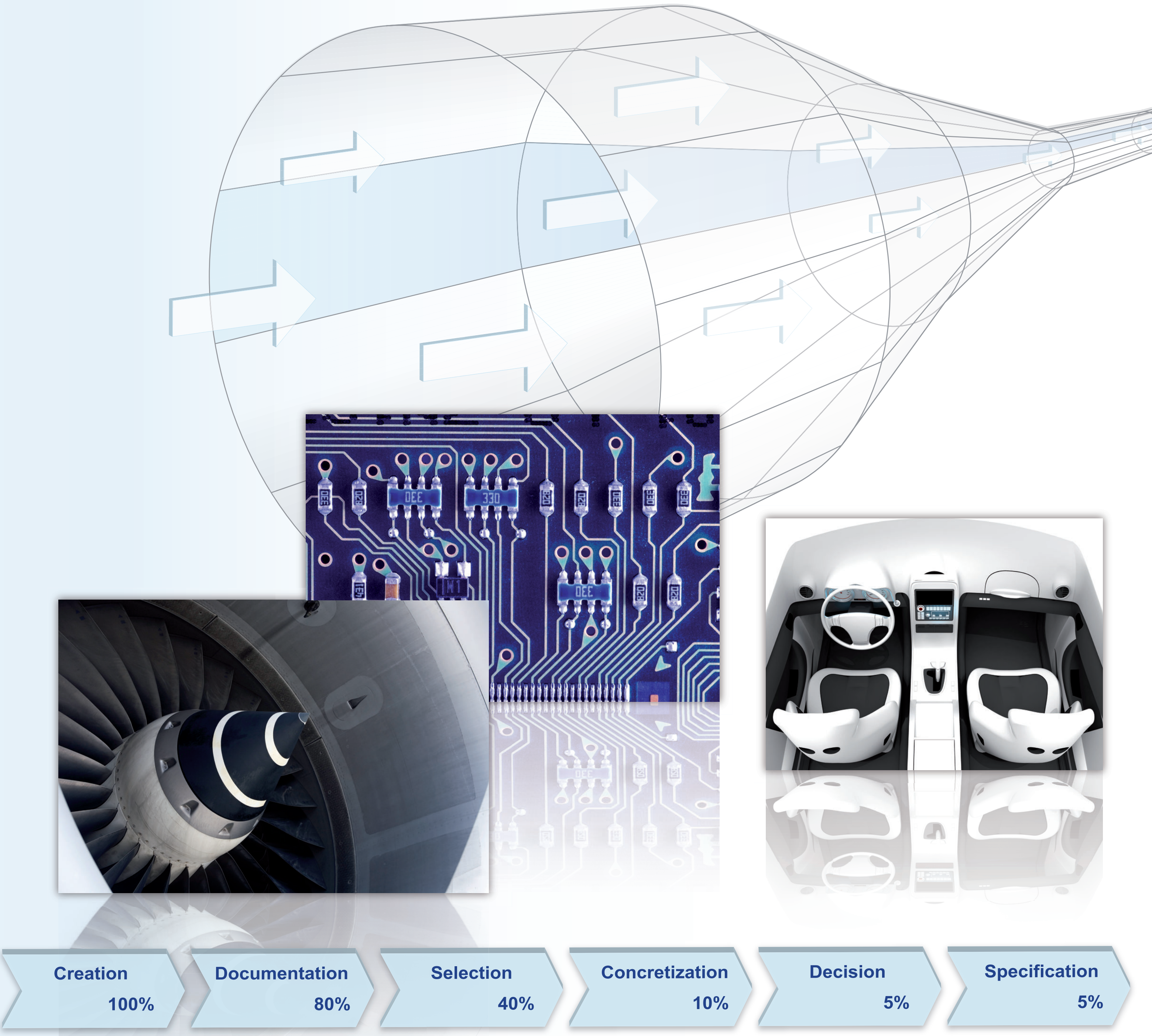
Thinking ahead the Future of Additive Manufacturing –

Future Applications



DMRC
DIRECT MANUFACTURING RESEARCH CENTER

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Imprint

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Preface

Additive Manufacturing (AM) technologies refer to a group of technologies that build physical objects directly from Computer Aided Design (CAD) data. Basically, AM-technologies work layer-by-layer with liquids, sheet or powdered materials. Due to this, there are a number of interesting opportunities and advantages, as e.g. freedom of design for manufacturing parts of almost any arbitrary complexity.

Several technology platforms, e.g. MANUFUTURE Europe, address the strengths of these technologies as future research targets of manufacturing technologies. Examples for those research targets are sustainable manufacturing and Information and Communication Technique (ICT)-enabled intelligent manufacturing, to name just a few. From this point of view, AM has the potential to revolutionize manufacturing processes in various industries. Nevertheless, there are still open research fields to be investigated. The Direct Manufacturing Research Center (DMRC) strives to close this gap.

The DMRC is a proactive collaboration of key technology suppliers and forward thinking users who have a common interest in advancing AM-technologies from Rapid Prototyping to dependable Direct Manufacturing (DM) technologies. DM implies manufacturing parts which meet the mechanical requirements and can be directly used. An essential prerequisite for the successful establishment of DM will be the awareness of its fascinating capabilities among industrial operators. Concurrently, providers of AM-technologies have to be aware of specific customer demands and the general framework in user industries, e.g. certification processes, to optimally fulfill customer demands with the right products. This is the starting point of the project ''Opportunities and Barriers of Direct Manufacturing Technologies within the Aerospace Industry and adapted others“. This project is conducted by the Heinz Nixdorf Institute in cooperation with the DMRC. The goal are three studies, lining out opportunities and barriers of DM-technologies in selected industries.

The present study is the second study conducted under the auspices of the DMRC. It focusses the strategic planning for future DM-applications in the aerospace, automotive and electronics industry, as these were assessed to entail the highest potential for a broad-scale implementation of DM. The study reveals a wide range of possible applications and deduces future requirements on DM-technologies.

Our thanks go to all experts who have supported the DMRC in the creation of this study, especially to Prof. Dr.-Ing. J. Gausemeier and his team from the chair for Product Engineering at the Heinz Nixdorf Institute.

Best regards

Martin Schäfer

Corporate Technology
Siemens AG Corporate Research and Technologies

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Introduction

The present study is the second of three public studies, resulting from the project "Opportunities and Barriers of Direct Manufacturing technologies within 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 tool-providers of the DMRC can significantly benefit from the strategic planning of future applications, as it serves as a support to convince their customers to use DM-technologies extensively.

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

Proceeding in the Project

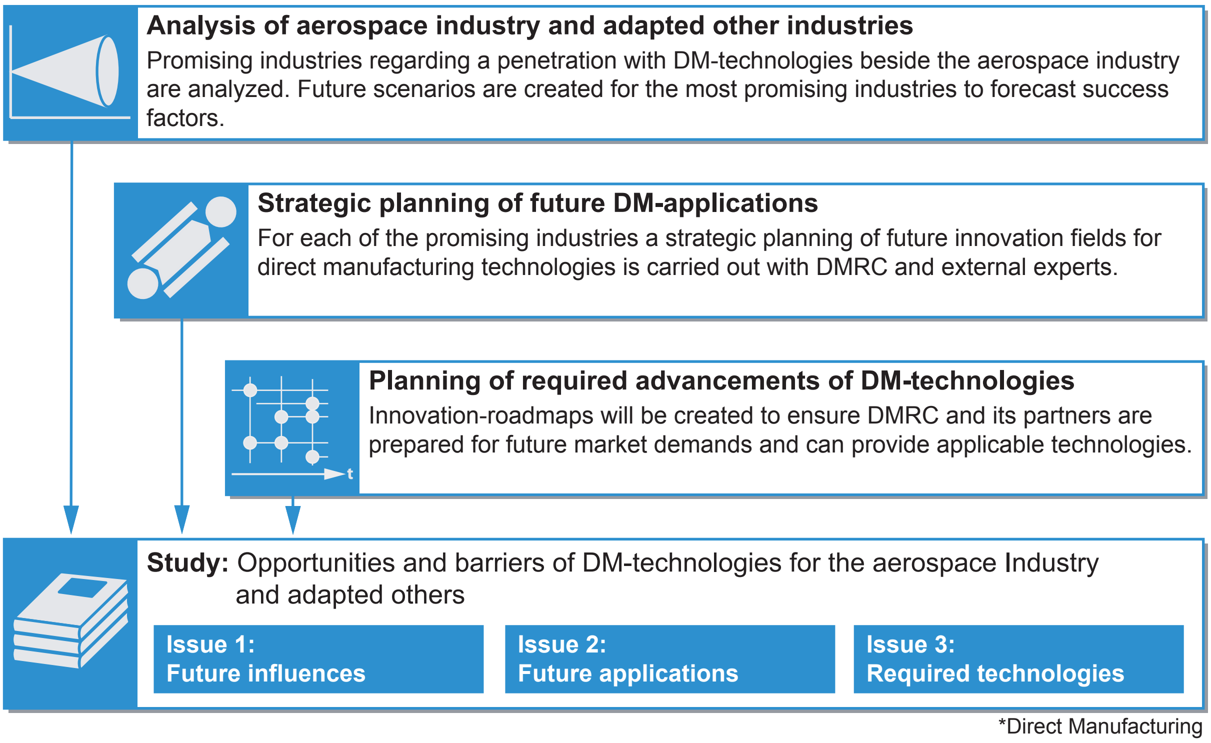


Figure 1: Proceeding in the project

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 are chances, risks and future success factors for embedding DM-processes into the production of these industries?

For this purpose, promising industries are assessed regarding a penetration with AM-technologies in 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 for 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 manufacturing technologies have the potential to fulfill the requirements for DM in the future?
- Which technological advancements have to be realized to tap the entire potential of DM?
- When can the developed applications be manufactured using DM, as technological advancements will have been realized in accordance to future requirements?

Therefore, advancements of existing AM-technologies will be 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 within the project. The public studies cover three issues, each respectively comprising an overview of one work package. The studies will be released during the project.

The first study “Thinking ahead the Future of Additive Manufacturing – Analysis of Promising Industries“, comprising an overview of work package 1, has been released in May 2011. An electronic version of the first study is available on the DMRC web site.

Proceeding in Study

The present study provides the outcomes resulting from work package 2. It reveals ideas for future applications of AM-technologies. In addition, the study comprises current and future requirements to advance AM-technologies from Rapid Prototyping to DM-technologies. The main results of the work package emerged from several workshops at the Heinz Nixdorf Institute, Paderborn, Germany and at Boeing, St. Louis, USA. A total of over 40 experts from the DMRC and external companies contributed their knowledge.

This study focuses on work package 2.

The first chapter focuses on the *Business of Additive Manufacturing*, summarizing the main results of work package 1. This comprises the Business of Today and the Business of Tomorrow for the aerospace, automotive and electronics industry. The Business of Tomorrow describes the selected reference scenarios for these three industries, focusing aircraft production, automotive production, and electronics industry manufacturing equipment, as well as the reference scenario for the global environment.

Chapter one covers the business of today and the business of tomorrow.

The second chapter covers *Future Applications of Direct Manufacturing*. The selected reference scenarios were used as an impulse for product discovering. Against this background, ideas for future applications were developed within creativity workshops with experts from the Direct Manufacturing Research Center and external experts from each industry. The identified applications were pooled to innovation fields, which were ranked according to their chances and risks. Moreover, requirements, which the identified applications impose on DM-technologies, were deduced. The innovation fields selected as the most promising for the application of DM in future were concretized through realization and implementation studies within specific workshops and through market research.

Chapter two encompasses future applications of DM.

The third chapter presents the results of the expert survey on *Current and Future Requirements on DM-technologies* in order to validate the requirements deduced from the innovation fields and to reveal the most important requirements.

Chapter three presents the results of the expert survey on requirements on DM.

The final chapter summarizes the study and provides an outlook for the further proceeding in the project.

Chapter four provides a conclusion and an outlook.

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 (bold printed) summary. A short description regarding the methodological approach is provided at the beginning of each chapter.

Management Summary

The present study comprises three parts. Firstly, current application fields of AM in the aerospace, automotive and electronics industry are analyzed, to gain an overview of the current market penetration with AM-technologies. Based on this, future scenarios are developed to deduce future success factors. This allows the AM-industry to be prepared for the business of tomorrow. Secondly, ideas for future applications of DM in the aerospace, automotive and electronics industry are developed and specified, and resulting requirements on DM are deduced. Finally, the identified requirements were validated in an expert survey to identify the most important requirements and technology advancements that are necessary for the realization of the identified (future) applications. This enables the AM-industry to develop and pursue consistent technology strategies and to bundle available competences to effectively advance AM-technologies to DM-technologies.

The Business of Additive Manufacturing

AM increasingly finds its way into production processes of various industries.

The analysis of the *Business of Today* indicates that AM is progressively gaining importance, as it opens up new opportunities in many instances. Various industries are seeking for ways how to capitalize on the benefits AM provides, such as the freedom of design; new industries are becoming aware of these benefits. In particular the aerospace industry, which produces geometrically complex high-tech parts in small lot sizes, can benefit from AM's flexibility. Therefore, already today the aerospace industry is in the vanguard of the industrial application of AM. Progressively, AM-technologies are also being applied in the automotive and electronics industry.

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

As a result, these three industries were outlined as particularly auspicious for the Business of Tomorrow of AM. To delineate future prospects and threats for possible beneficiaries of AM, both, branch scenarios, focusing the aircraft production, automotive production and electronics industry manufacturing equipment, and scenarios for the global environment were developed and combined to overall scenarios.

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

The most probable scenario combination for the aerospace industry with the highest effect on the aircraft production describes a future, where Europe sets the pace in a globalized world. The aircraft production is characterized by individual customization of aircraft which fosters the application of AM-technologies. Due to the successful part implementation, additively manufactured parts start to be associated with high performance and high quality. To be successful in this future, it will be necessary to build up general ground rules for the design of secondary aircraft structures, systems etc. for AM-technologies and to flow them down to suppliers.

Future of automotive production: New production concepts and individuality require improved productivity and quality of AM.

The future of automotive production is characterized by new production concepts that drive the 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 additively manufactured parts.

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

In the future of the electronics industry manufacturing equipment, highly integrated production systems for individualized production prevail. In this world, 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 competences. To succeed in a future that is characterized by highly integrated production, the production has to incorporate AM.

Future Applications of Direct Manufacturing

120 application ideas in 27 innovation fields were developed.

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* have been identified as 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 the 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 the application of DM.

- **Handling of Fluids** describe parts that focuses 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 reduction.
- **Optimized Tooling** include ideas for integrating 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 achieved.

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** 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.
- **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.

The innovation fields were used to deduce requirements on DM-technologies.

To enable AM-technologies for DM in the identified future applications, it is necessary to align the technology development with current and future requirements. This enables the AM-industry to develop and pursue consistent technology strategies and to bundle available competences to effectively advance AM-technology into dependable DM-technology. Therefore, the developed innovation fields are analyzed in detail to deduce requirements on DM. High process stability, certification, design rules and the ability to control the part quality during the production process represent basic requirements across the most innovation fields, just to name a few. Besides the technology-specific requirements, general requirements that relate to companies' performance, e.g. high innovation ability, were identified.

High process stability, certification, design rules and on-line quality control processes are decisive for the most innovation fields.

Future Requirements on Direct Manufacturing

The identified general and technology-specific requirements were validated in an expert survey in order to identify the most important requirements and the companies' and AM-technologies' performance concerning these requirements.

With regard to the general requirements, the overall assessment shows that the significance of all listed requirements will increase in future. In addition, all requirements are and will continue to be more significant for machine manufacturers than for material suppliers. High innovation ability has the highest significance today, for both, machine manufacturers and material suppliers, and will be the most significant requirement in future. Strong problem solving competences currently have a relatively small significance, but its significance will immensely increase in the future for both groups. For machine manufacturers, a continuous IT-support has the largest deviation between current and future significance. For material suppliers, a distinct customer orientation will be crucial for the business of tomorrow. Therefore, especially with regard to these requirements, there is a need for action for machine manufacturers and material suppliers, respectively.

High innovation ability is crucial for material suppliers and machine manufacturers.

The overall assessment of the technology-specific requirements shows that the significance of these requirements will increase in future. The following requirements are assessed to be outstanding for the penetration of AM in future:

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

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 processable shape memory alloys;
- Automated integration of AM-machines into existing production lines;
- Highly integrated AM-machines.

However, there are considerable discrepancies between the requirements deduced from developed innovation fields and the experts' assessment of the requirement's significance. For instance, larger build-chamber volumes are required for the realization of a large number of product ideas developed for the aerospace and automotive industry, such as morphing structures or functional body-in-white, respectively. However, according to the experts, a build chamber volume sized larger than 8 m^3 is not expected to be significant in future.

Today: The significance of the requirements and technologies' performances largely correlate.

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

The significance of the technology-specific requirements largely correlates with the technology's degree of performance across all considered technologies. As the vast majority of the requirements will gain significance, they are likely to turn into critical requirements if no technological advances will be achieved. Some requirements, such as build-up rates > 100 cm^3/h, are already considered as almost critical today. Therefore for instance, research that contributes to the production speed could promote AM-technologies in future. The amount of research that has to be conducted to meet a requirement sufficiently strongly depends on the individual technology. For example, an adequate availability of materials with self-healing properties requires much more effort in development, than increasing process stability to a sufficient level.

1

The Business of Additive Manufacturing

In the study “Thinking Ahead the future of Additive Manufacturing – Analysis of Promising Industries”, 14 current application fields were analyzed from market and technology perspective in the context of AM [GEK+11]. The aerospace, automotive and electronics industry were outlined as particularly auspicious for the business of AM.

The aerospace, automotive and electronics industry are particularly auspicious for the business of AM.

This chapter gives an overview of the business of AM and its development towards DM. The business of today encompasses the development of AM from its beginning until now and the analysis of the aerospace, automotive and electronics industry (chapter 1.1). The business of tomorrow is drawn by the developed scenarios for these three industries (chapter 1.2). The chapter concludes with the scenario transfer addressing future chances, risks and success factors deduced from the developed scenarios (chapter 1.3).

1.1 The Business of Today

The following sections cover the development of AM and short characteristics of the today’s penetration of the aerospace, automotive and electronics industry through AM.

1.1.1 What is Additive Manufacturing – Development from its beginning until now

AM describes the layer-wise creation of parts based on an electronic data set, which is usually derived from a 3D-CAD model. Contrary to conventional subtractive manufacturing techniques, such as milling, AM generates parts by adding material in ultra-thin layers, without using any tools and molds. The geometrical and structural complexity and individuality of additively manufactured parts is limited by nearly nothing but the used CAD-model. This principle of *Freedom of Design* enables injection molding tools with integrated spiral cooling channels whose production previously was inconceivable, and individually shaped, miniaturized hearing aids, just to name a few applications.

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 a 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 (Selective) Laser Sintering laid the foundation for AM in the 1980s. At an early stage, the technologies were used to quickly create physical prototypes using polymers. The term **"Rapid Prototyping"** refers to this kind of applications. With increasing technological degree of maturity, AM is also being used for the production of injection molding tools, which is known as **"Rapid Tooling"**. For this purpose, special composite metals were developed [Gep07].

Recently however, a growing number of industries have been realizing the promising potentials of AM and benefit from the advantages of AM-technologies. In the last decade the market has grown by an average of 18% per year. Currently, the total volume amounts to $1.325 billion [TMW11-ol], [Woh11]. As additively manufactured parts increasingly meet the requirements of various industries and can be applied immediately after production, AM is progressively pushed from Rapid Prototyping towards small series production – the so called **"Direct Manufacturing"**.

Aerospace industry is a pioneer in using AM.

In particular the aerospace industry is in the vanguard of the industrial application of AM, and especially benefit from AM's flexibility to produce geometrically complex high-tech parts in small lot sizes. AM is also widely spread within the medical sector, including dental applications, prostheses, implants etc. AM is also being applied within the capital goods industry, e.g. in the armament, automotive, electronics as well as in the tool- and mold-making industry. Even, consumer industries such as the sports, textile, furniture, toys or the jewelry industry are becoming aware of the great advantages of AM for their business. AM in terms of DM is not prevalent yet, experts however insist on its huge potential.

In some fields of application, AM is used in order to shape complex parts, for instance designer lamps or pendants in the jewelry industry. Within other industries, AM enables functional integration, such as double walled structures which are being 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 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.

To tap the full, extraordinarily high potential of **"Direct Manufacturing"**, a close cooperation between application-oriented research focusing material and technology development, and users of AM-technologies is mandatory. For this purpose, the Direct Manufacturing Research Center (DMRC) was founded. The major goal is to advance AM-technologies into dependable, production rugged Direct Manufacturing technology (DM).

In the following, the aerospace, automotive and electronics industry are analyzed in detail.

1.1.2 Aerospace industry

Aerial transportation has never been as important as today, and will likely play a key role in the future as well. The spectrum ranges from unmanned aerial vehicles (UAV) and transport aircraft to vehicles for space tourism.

Today, the aerospace industry has to meet various requirements for instance regarding environmental compatibility. In addition, the industry has to cope with increasing crude oil prices. Therefore, the aerospace industry continuously endeavors to increase efficiency of aircraft and to reduce air pollution, noise exposure and raw material consumption [Bul09].

Concerning the application of DM-technologies, the aerospace industry shows a huge potential. This is mainly due to the fact that aircraft often require strong and geometrically complex parts which in turn are especially lightweight. These parts are produced in small quantities at comparatively high costs per unit. Therefore, the aerospace industry already is a pioneer in the DM-business today. For instance, global players like Boeing and Airbus are already applying DM-technologies; small companies are expected to follow this trend [Wor10], [Wor11a], [GEK+11].

Today, the share of the aerospace industry of the global AM-market volume amounts to 9.9%, which equals $131 million [Woh11]. Compared to the expected world market volume of the aerospace industry amounting to $598 billion in 2011, the AM-market share is still marginal [RE11].

AM increasingly matches the requirements of the aerospace industry.

However, as parts manufactured by AM-technologies progressively meet the requirements of the aerospace industry, the range of additively manufactured products directly applied in aircraft is quite diverse at present. This in turn enables a far easier and even faster assembly and reduces inventory stocks since complex and movable geometries can be manufactured on demand. Furthermore, manufacturing processes are optimized as components can be manufactured in one piece. Thereby, joining processes can largely be eliminated [BLR09].

Exemplary parts that have already been manufactured additively are:

- Structural parts, different tools or models [Woh10];
- Thrust reverser doors and acoustic panels by Royal Engineering Composites [REC11-ol];
- Landing gears by EADS [ASA11-ol];
- The gimbal eye, or camera, rotates electromechanically on two axes by Stratasys Inc. [STR11a-ol].
- Swirler: fuel injection nozzle for gas turbine applications by Morris Technologies, Inc. (see fig. 1-1).

Figure 1-1: Swirler (fuel injection nozzle) for gas turbine applications made from CobaltChrome MP1 (picture courtesy of Morris Technologies, Inc.*) provided by* EOS.

Additionally, AM-technologies are used for reparation and remanufacturing of worn component parts, such as turbine blade tips and engine seal sections [Ree09a], [Wor10].

1.1.3 Automotive Industry

In the automotive industry, the integration of customer requirements is decisive.

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]. However, customer demands on design, environment, dynamics, variability, comfort, safety, "infotainment", cost effectiveness and sustainability converge in a melting pot of challenges and determine who will succeed in this highly competitive market [Bul09].

In order to meet these challenges, the automotive industry is a pioneer in applying innovative technologies in many instances. Since 2000, AM-technologies have also found their way into automotive production. In 2010, the automotive industry contributed 17.9% to the total AM-market volume which corresponds to $240 million [Woh11]. Together with the motorsports industry, the automotive industry counts the second largest market volume after the consumer products/electronics industry. However, compared to the world-wide automotive industry market volume of $2.6 trillion, this share is still marginal [SZW11-ol].

AM is used for Rapid Prototyping and small series production.

Currently, AM-technologies are usually applied in terms of Rapid Prototyping of functional models. Small, complex and non-safety relevant parts for luxury and antique cars are already manufactured directly. The vast majority of these parts are produced in small series, as process reliability and repeatability are still limited [BLR09], [Fro07].

The motorsports sector constitutes an important field for the application of AM-technologies, especially as a link between the automotive sector and the aerospace industry; knowledge gained from high-tech aerospace parts is increasingly transferred to future applications in the motorsports sector as here high performance and weight reduction also play an important role [EJN11-ol].

Some examples for notable current applications of AM-technologies in the automotive industry are:

- Intake valve and other parts of the engine bay, gearbox and engine components by Mini John Cooper Works WRC [LL11-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];
- Ducati engine by Stratasys Inc. (see fig. 1-2)

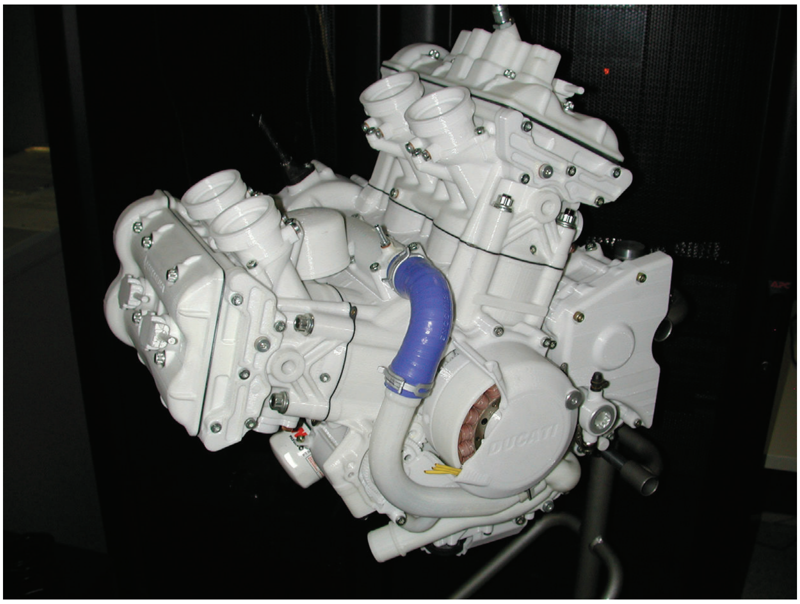


Figure 1-2: Ducati engine made by Fused Deposition Modelling (picture courtesy of Stratysys, Inc.)

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].

1.1.4 Electronics Industry

Electronics industry's products are characterized by rapid development.

The electronics industry is present in daily life in many instances as electronic products can be found in a broad variety of applications, e.g. in mobile phones, computers, cars etc. Therefore, a variety of tied industries is affected by the developments in the electronics industry. Furthermore, there is a high demand for flexibility in the electronics industry due to rapid technological advance and the continuously shortening life cycles of electronic products. In addition, the electronics industry's tendency to miniaturization and smart micro systems have increased the need and importance for functionally integrated structures [Bul09], [Fro07].

Due to these characteristics, the electronics industry can benefit significantly from AM, as development processes and build times can be accelerated immensely. Additionally, AM enables functional integration and embedding electronics into all kind of geometries.

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 processable materials such as new polymers, and metals and inks has been emerging [SA10]. Especially, the production of manufacturing and tools equipment benefits from the deployment of AM. Here, in particular, 3D-printing methods are pioneers due to the high ability to include electrical circuits into work pieces. So far, a variety of electronic parts have already been produced with AM-technologies, such as:

- 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 Kunstoff-technik [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).

Additionally, spare parts for high-tech electronic components are increasingly produced additively, whereby render tooling and storage become obsolete [Wor11c].

Figure 1-3: Gripper made by Fused Deposition Modeling (picture courtesy of STRATYSYS, INC.*)*

1.1.5 Current Success Factors

Current success factors: design rules, surface quality, process repeatability, part reproducibility and certification

Each industry places its own demands on its manufacturing technologies. Ultimately, different success factors are decisive for the establishment of AM within the analyzed industries. Success factors are factors, which significantly influence the success of a business (buying factors). In general, these factors differ for various industries. However, the overview of the identified success factors from today's point of view has shown that most success factors are relevant for many of the analyzed industries. Especially critical success factors for an extensive diffusion of DM from today‘s perspective are: the definition of design rules, surface quality, process repeatability and part reproducibility, and the certification of manufacturing processes.

1.2 The Business of Tomorrow – Thinking ahead the Future of Additive Manufacturing

"Don't worry about the future; it will not begin until tomorrow."
– Žarko Petan

To ensure success for the Business of Tomorrow, it is necessary to timely seize opportunities from technological and market developments.

Companies from capital goods industries are confronted with a rapidly changing technological, political and social environment. While product life cycles are shortening, companies have to introduce (future) promising product innovations within a shorter time in order to be successful in global markets [GPW09]. Therefore, it is necessary to recognize and coordinate the opportunities from technological and market developments on the one hand, and to anticipate threats for the established business of today on the other hand.

Innovative products result from a complex product engineering process that stretches from the product or business idea to the successful product launch. Our experience proves that the product design process cannot be regarded as a stringent sequence of process steps. Instead, it rather involves a three-cycle model as shown in figure 1-4.

Product Engineering process

The first cycle revolves around ***Strategic Product*** and ***Technology Planning***, and includes activities ranging from the identification of future success potentials to promising product concepts. The second cycle encompasses the actual ***Product Development***, where several domains such as mechanics, electronics, software etc. work together on one product. Parallel to the product development cycle, the cycle of the ***Production System Development*** deals with the engineering of the manufacturing system.

The first cycle of the introduced three-cycle model covers the tasks of *Foresight, Product Discovering* and *Business Planning*.

- **Foresight** aims at the determination of future success potentials and the deduction of appropriate business opportunities and fields of action. Therefore, methods like the scenario-technique, Delphi studies or trend analyses are used. Foresight is object of the first study, see [GEK+11]. This chapter summarizes the main results.

- **Product Discovering** concentrates on the retrieval and selection of new product/service ideas based on the detected success potentials. This is object of chapter 2 in this study.

- **Business Planning** initially deals with the business strategy, i.e. answering the question which market segments should be covered, when and how. Based on this, the product strategy and a business plan are elaborated. The business planning is not part of the project/study.

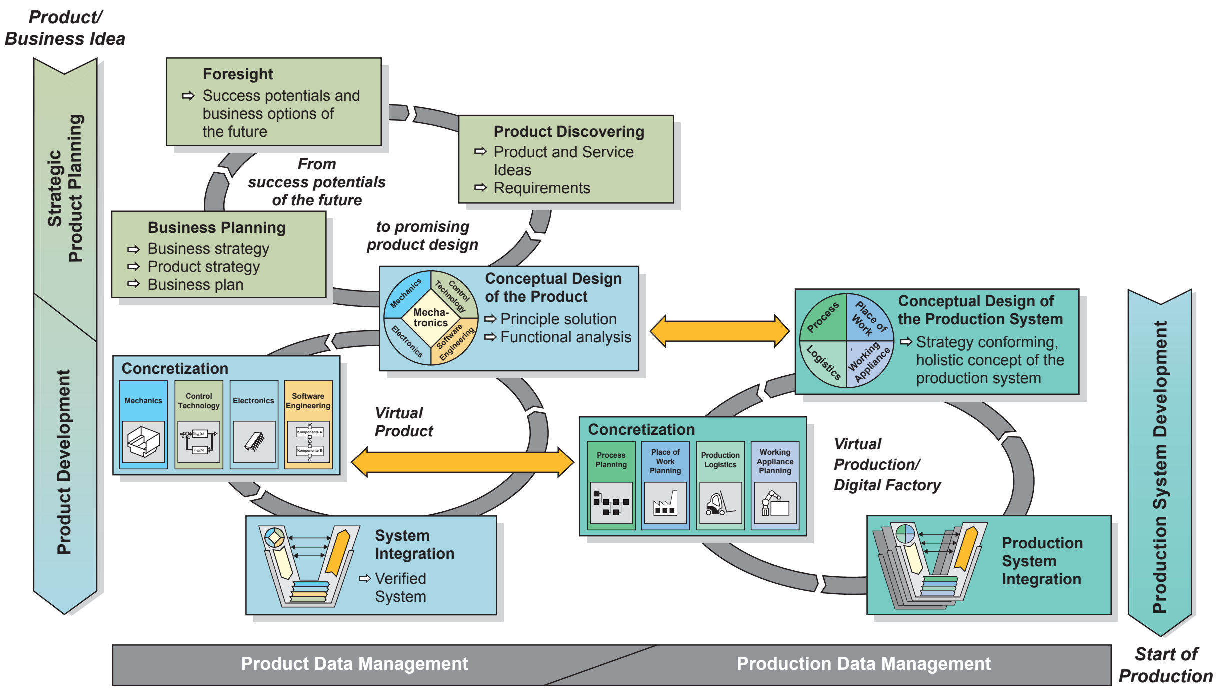


Figure 1-4: The 3-cycle-model of Product Engineering [GPW09]

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. Thereby, DM-technology providers get an idea of how the areas of application for their products may look like in future. The scenario-technique is a suitable tool for that kind of systematic foresight and the detection of future success potentials. Using the scenario-technique, future scenarios for the global environment as well as 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. In the next step, the scenarios for the global environment and the branch scenarios were matched to overall scenario combinations. This chapter presents and illustrates the selected reference scenarios. A detailed description of all scenarios is part of the confidential study.

1.2.1 Global environment

The developed global scenarios describe possible future situations of the broader environment in the context of AM. These scenarios encompass statements on politics, economy, society and environment. For characterizing the global environment, 17 key factors were used [GEK+11]. Based on the future projections of these key factors, three global scenarios were developed. In the following, the selected global reference scenario **"Europe Sets the Pace in a Globalized World"** is described. Figure 1-5 provides a visualization of this scenario.

17 key factors were used to develop three consistent scenarios for the global environment in 2020.

Figure 1-5: Visualization of the reference scenario for the global environment "Europe Sets the Pace in a Globalized World" (pictures courtesy of: see picture credits)

Politics

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

Increasing influence of strong and transparent 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. European universities now have an excellent international reputation, and most of them internationally rank among the top 100. The broad majority of the population is well skilled, the unemployment rate is relatively low, and the labor market is nearly balanced. Nevertheless, as increasingly more elderly people are retired from work and fewer young people move up, many companies have great difficulties to find just enough staff. This cannot be justified by lack of qualification; there is still a labor deficit.

The efficient and highly effective policy strengthens the role of the EU. In addition, prosperity is fostered through European integration. This development facilitates the foreign trade: free trade without borders is possible within the EU. Protection of technological advances is proceeding slowly. Until today, only short-term protection against product piracy is possible, as product protection has become a greyhound racing between original manufacturers and product pirates. Due to recent developments, huge steps are being made to stem product piracy.

Economy

European economy grows due to value-creation-intensive enterprise functions.

Due to the great image and high attractiveness of the EU as a high-tech location, many enterprises 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 development enables the EU to expand its degree of globalization. European states have become key players and pacemakers of the globalization, as they succeeded to steadily increase their exports to Asia and America. Due to these developments, the EU has recovered well after the economic crisis, and has returned back to a strong organic growth; the gross domestic product is growing by 2% annually. This development has been stable for years.

Society

Strong tendency towards urbanization

In the past years, slight population growth through migration occurred. Due to good living and working conditions, the number of immigrants has been rising continuously, whereas the number of EU inhabitants has been declining. Children and family have a high priority; however, there still is a birth deficit. Older people feel needed, and are willing to work longer. 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 jobs and entertainment possibilities. In contrast, a tendency towards the 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.

To adjust differences in income, an unconditional basic income has been introduced by law in the EU, despite initial skepticism. The governments pay every inhabitant the basic income without any repayment claims.

Awareness for highly sustainable mobility

Additionally, the awareness for highly sustainable mobility is emerging. Means of transportation stand for freedom and independence. The image of sustainable development has led to a boom in the ecologically reasonable means of transportation. Due to this development as well as to the availability of modern digital forms of communication, new virtual mobility is propagating increasingly. People interact with each other through chats, forums and video conferences. However, the importance of personal contact has remained relatively high.

Environment

The restrictive behavior of the OPEC is unbroken and the capacities of the conveyors are just enough to meet the world's demands. Therefore, scarce energy fosters high efficiency. Until now, the EU has not succeeded to free itself from its dependency on the world energy market. Although the worldwide application of sustainable and intelligent processing of raw materials as well as better recycling processes were expected to provide a reduction in demand, the raw material market is recovering just slowly.

Efficient use of material and regenerative energy prevent energy crisis.

However, raw material bottlenecks still can 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.

1.2.2 Aerospace Industry

13 key factors were used to develop three consistent scenarios for the aircraft production in 2020.

For the aerospace industry, the aircraft production has been selected as the most promising field. The developed scenarios encompass statements on suppliers, market, branch technology and regulations. The future of the aircraft production is described by 13 key factors [GEK+11]. Using future projections of these key factors, three scenarios for the aircraft production were developed. These were matched with those for the global environment to create overall scenarios. The scenario **"Individual Customization Fosters Additive Manufacturing Technologies"** fits in perfectly with the selected reference scenario for the global environment, and was selected as reference scenario for the aircraft production. In the following, this scenario is described in prose and visualized in figure 1-6.

Figure 1-6: Visualization of the reference scenario for the aircraft production "Individual Customization Fosters Additive Manufacturing Technologies"

Suppliers

Intense cooperation between mega suppliers and aircraft manufacturers.

The cooperation between aircraft manufacturers and suppliers within the aircraft industry has changed significantly, since partnerships with suppliers have been established. More responsibility has been transferred to suppliers; the increasing cooperation and communication (collaboration) between manufacturers and suppliers is good; the suppliers contribute their own ideas to solve problems and develop all components under constant consultation with the manufacturer. Simultaneously, the market accessibility for suppliers has changed considerably. Today, mega suppliers rule the market: 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

Increasing number of variants

Until recently, the usage of interior variants due to branding purposes has still been common. As a reaction of this continuing marketing trend, aircraft manufacturers have increased their number of variants, and each aircraft is progressively getting individual.

Branch Technology

AM-parts are progressively used for safety relevant parts.

As parts produced by AM-processes started to be associated with high performance and high quality, many manufacturers jumped on board, and started to invest into these technologies. For instance, additively manufactured parts are used for critical parts or for low scale production. Due to the successful part implementation, AM-technologies are incrementally on the rise, and investments into further research are made. As a result, many new materials enter the market (technology-push). These new materials have excellent properties which promise lower production costs and can probably be used for the implementation of new technologies (market-pull meets technology-push).

Part properties have become tailor-made.

Furthermore, new materials/machines allow the customization of material properties, as tailor-made part properties have become possible by now. Intense research and new developments in AM-technologies even provide further progress in AM-processes. As the ratio of functionality and costs has been improved, 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. The reduction of required workforce to perform manual work was additionally supported by substantial advancements in the development of machines which are now mainly used for the highly-automated processes. These machines can substitute hand-crafted steps. In addition, there is a high need for energy-efficient aircraft as scarcity of resources proceeds. Higher efficiency rates 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, the acceptance of AM-standards is increasing: the elaborated standards are described in a common set of standards. Due to the commitment of almost all aircraft manufacturers and many suppliers to use AM-technologies within aircraft production, certification institutions have recognized the importance of the technologies; a common understanding in the value chain has been created. Furthermore, requirements for noise reduction push AM-technologies. Newly developed materials and innovative as well as industrial-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 most probable future scenario combination for the aerospace industry with the highest impact on its field of conception describes a world, where Europe sets the pace in a globalized world. The scenario for the aircraft production is characterized by individual customization of aircraft which fosters the application of AM-technologies.***

1.2.3 Automotive Industry

13 key factors were used to develop three consistent scenarios for the automotive production in 2020.

The automotive production has been selected as the focus for thinking ahead the future within the automotive industry. The developed scenarios encompass statements on suppliers, market, branch technology, automotive concepts and regulations. The future of the automotive production is described by 13 key factors [GEK+11]. Based on future projections of these key factors, three scenarios for the automotive production were developed. These were matched with those for the global environment to create overall scenarios. The scenario **"New Production Concepts Drive Individuality"** fits in perfectly with the selected reference scenario for the global environment, and was selected as reference scenario for the automotive production. In the following, this scenario is described in prose and visualized in figure 1-7.

Figure 1-7: Visualization of the reference scenario for the automotive production "New Production Concepts Drive Individuality"

Suppliers

High competition requires cooperation between suppliers and manufacturers.

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 production is growing in order to save logistic costs. On the other hand, a worldwide localized production is still on demand in order to guarantee a fast global parts supply. In addition, the value-added distribution has changed significantly. 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.

Market

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

Green production and spare part business are of high importance.

Branch Technology

An intense material research has led to new materials for the automotive industry. Today, high-tech materials are widely used as they provide overwhelming qualities. The increased competition led to lower prices which resulted in a highly growing demand. Furthermore, AM in series production is possible by now, and functional-driven design is the key to success. Parts designed for AM are only produced in small lots and they are mostly small in size, whereas most automotive parts are still designed production-technology-driven in order to minimize production costs. Hence, production-technology and functional-driven design are teamed. Single parts are built just in time in order to keep up the existing schedule. In addition, a tendency towards a high scalability in the whole production process occurs; the assembly lines increasingly consist of highly flexible robotics equipped with different tools.

AM prevails in series production for small lot sizes.

Automotive concepts

The role of the automobile in society is ambivalent. Although prestige and the need for individuality still play an important role for the buying decision for a new car, emotionality partly yields to pragmatism regarding some customer groups. Therefore, two different future car concepts are prevailing: the individualized high-tech car and the conventional mass car. OEMs have huge problems to fulfill the individual requirements, and core customization raises the costs along the whole value chain, which has made cars more expensive than ever before [Abd08], [RB09-ol]. Therefore, individualized production is being combined with modularized customization.

Individualized high-tech cars and conventional mass cars dominate the market.

Regulations

Due to the commitment of almost all automotive manufacturers and many suppliers for using AM-technologies within automotive production, certification institutions recognized the importance of the technologies; common requirements for the certification of additively manufactured parts were defined widely. Manufacturers adjust their new products to these requirements. Despite the increasing level of certification, still partly varying levels drive costs and prevent an extensive use within the automotive production; finished parts as well as whole processes (material powder, machine, etc.) need to be certified with high effort. At the same time, alternative power train concepts calm down the discussion on legislation on fuel consumption.

Certifications are available; varying levels drive costs.

The most probable future scenario combination for the automotive industry with the highest impact on its field of conception describes a world, where Europe sets the pace in a globalized world. The scenario for the automotive production is characterized by new production concepts that drive the individuality of automotives.

1.2.4 Electronics Industry

13 key factors were used to develop three consistent scenarios for the electronics industry manufacturing equipment in 2020.

For the electronics industry, the manufacturing equipment has been selected as the focus to think ahead the future. The developed scenarios encompass statements on suppliers, market, branch technology and regulations. The future of the automotive production is described by 13 key factors [GEK+11]. Using future projections of these key factors, three scenarios for the electronics industry manufacturing equipment were developed. These were matched with those for the global environment to create overall scenarios. The scenario **“Highly Integrated Production Systems Allow Individualized Production“** fits in perfectly with the selected reference scenario for the global environment, and was selected as reference scenario for the automotive production. In the following, this scenario is described in prose and visualized in figure 1-8.

Figure 1-8: Visualization of the reference scenario for the electronics industry manufacturing equipment “Highly Integrated Production Systems Allow Individualized Production“

Suppliers

Value added networks have been emerging.

Today, manufacturers are strongly cross-linked within the electronics industry as value-added networking has been proven as an appropriate method to mutually increase competencies. Networks between global and regional operating manufacturers evolve.

Market

Individual production systems are on the rise.

The increasing complexity of tool manufacturing projects fostered a closer networking with customers; customer influence is on the rise. Due to the growing demand for individual, customized products, innovation is considered to be the key for success within the electronics industry, and many manufacturers committed themselves to innovation. The resulting high innovation speed is progressively shortening product life cycles. As customers are willing to pay higher prices for the individuality, the number of orders that are accepted beneath the cost-recovery has been immensely reduced, compared to 2011, and the price pressure on companies has been decreasing. Due to these developments, individual production systems prevailed. This leads to a very high product variety for the suppliers of manufacturing systems which is realized by a modular structure. The modularized customization of production systems is increasingly realized by software.

Branch Technology

Device-free production is partly established.

Progressively, intelligent processes and process monitoring prevail. These intelligent processes reduce the need for intelligent devices, and device-free production lines have been partly established within the electronics industry. Due to further research, improvements in AM-processes have been realized. Standardized design rules that are instrumental for part creation via AM-technologies have been developed and are continuously added. Today, functional-driven design is the key to success, as the ratio of functionality and costs has been improved. In addition, 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 productions systems. Highly flexible production systems are realized; life cycles of these production systems have extended.

Software takes over 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; these high-tech materials widely prevail.

Regulations

Certifications have prevailed; varying levels drive costs.

Suppliers and customers recognized the importance of AM-technologies. This forces certification institutions to define common requirements for certifying additively manufactured parts. Thus, a common understanding in the value chain has been established. In some exceptional cases, certification institutes established requirements in terms of new certification barriers. These varying levels of certification drive costs; (partly) finished parts as well as whole processes (material powder, machine, etc.) need to be certified with high effort.

The most probable future scenario combination for the electronics industry with the highest effect on its field of conception describes a world, where Europe sets the pace in a globalized world. In the scenario for the electronics industry manufacturing equipment, highly integrated production systems for individualized production prevail.

1.3 Scenario-Transfer – Future Chances, Risks and Success Factors for Direct Manufacturing

Within the scenario-transfer, the analysis of the scenarios for the selected industries takes place. Therefore, future chances and risks were deduced for the reference scenario combinations for the aerospace, automotive and electronics industry. Based on this, future success factors for the application of DM within the industries were derived. These constitute a profound basis for the development of strategic directions. Figure 1-9 provides an excerpt of the deduced chances and risks across all three considered industries. For more detailed information see the study “Thinking ahead the Future of Additive Manufacturing – Analysis of promising industries” [GEK+11]. All chances and risks are part of the confidential study.

Chances

- Individuality and customization foster AM-technologies: the ability for producing any part on one production system is improved, as multiple manufacturing steps can be performed by a single AM-machine
- Increased communication between manufacturers due to value-added networks can contribute to an intense research in AM-technologies, effective use of resources and the creation of new jobs
- Conventional transport can be reduced (data transfer is faster) and production takes place everywhere due to value-added networks
- AM-machines are mostly “plug and produce” manufacturing systems: as a higher range of products can be produced with the same machine, investments costs are reduced
- Due to the high flexibility of production systems, (spare) parts can be produced on demand
- A higher integration of AM-technologies in conventional manufacturing processes increases the fields of application for AM-technologies and the degree of value creation in a single process
- Functional-driven design is the key to success
- Due to new materials lifecycle costs can be reduced
- Additively manufactured parts require less raw material, as almost no waste will be produced
- Increased reproducibility fosters certification of AM-processes and increases the trust in AM-technologies, as safety-relevant construction jobs become possible
- Decreasing price pressure and greater customer interest foster market expansion and new products

Risks

- Functional-driven design is a challenge: High pressure to manage (limited ability of developers) and to meet functional requirements (limited ability of machines e.g. speed, product shape, etc.)
- High investments in certification, qualification of materials, processes, parts and personnel are necessary to keep up with standards
- Demand for part quality might grow faster than machine abilities; low quality of series parts may damage the reputation/image of AM-technologies
- Many new materials have to be qualified for existing machines, as they cannot be processed using AM-technologies
- Design rules for redesign processes of conventionally manufactured parts are required to enable them for AM
- Due to missing software standards, risk of software compatibility is high
- Tied-up capital increases, as the overall availability of materials has to be guaranteed
- Integration of multiple production steps increases dependence on AM-technologies and could, in case of failure, lead to a major shortfall of production
- Older engineers did not learn to create functional designed parts and may have restraints using this principle

Figure 1-9: Excerpt of the chances and risks deduced for the considered industries

Future Success Factors

Based on the chances and risks, future success factors have been derived. The following list is an excerpt; for more information see [GEK+11]; all factors are provided in the confidential study.

Certification is likely to turn into a central success factor for the AM-industry in future. On the one hand, it is important to agree on uniform certifications in order to strengthen trust in AM-parts. On the other hand, it is necessary to develop, facilitate and accelerate certification processes.

Qualification of personnel will be important, since especially engineers have to be educated to design functionally integrated parts (functional way of thinking). Additionally, people will have to learn to integrate AM-technologies into existing production processes.

AM-machines have to be enabled 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 integration of customers/customer requirements into product development processes, appropriate and fast processes have to be set up. Thereby, transparency and an even better customization can be achieved.

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 have to be developed.

AM-technologies have to be integrated into existing processes. Therefore, it will be necessary to increase the **Adaptability of AM-machines** with conventional production lines to higher the flexibility of production processes.

Strategic Directions

Based on the analyses of the reference scenario combinations for the three industries, strategic directions has been developed by the experts. For being successful in the selected future scenario for the aircraft production, an **integration of the supply chain** will be crucial. This implies building up general ground rules for design of secondary aircraft structure, systems etc. and flowing them down to suppliers. **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. For the electronics industry manufacturing equipment it will be necessary to enable AM-processes and AM-materials for **highly integrated production**.

1.4 Summary

Great efforts are done to improve AM-technologies' performance.

The analysis of today's business shows that AM is progressively gaining importance as it opens up new opportunities in many instances. Many industries are seeking for ways how to capitalize on the benefits AM provides, such as the freedom of design; new industries are becoming aware of these benefits. Therefore, great efforts are being made to improve the technology's performance regarding success factors such as build times, material and process qualification etc.

The aerospace, automotive and electronics industry were identified to be the most promising business opportunities for the application of DM in the future. For these three industries scenarios were developed, focusing the aircraft production, the automotive production and the electronics industry manufacturing equipment, respectively.

Strategic direction for the aerospace industry: Integration of the supply chain

The most probable future scenario for the aerospace industry with the highest impact on its field of conception describes a world, where Europe sets the pace in a globalized world. The aircraft production is characterized through individual customization of aircrafts which fosters the application of AM-technologies. Building up general ground rules for the design of secondary aircraft structures, systems etc. for AM-technologies, and flow them down to suppliers will be decisive for being successful in this scenario.

Strategic direction for the automotive industry: Increasing productivity of AM-processes and quality of AM-parts

The selected reference scenario combination for the automotive industry, also including the presented scenario for the global environment, is characterized by new production concepts that drive individuality of automotives. Against this background, it is necessary to increase the productivity of DM-technologies and the quality of additively manufactured parts.

Strategic direction for the electronics industry: Enabling AM-process and materials for highly integrated production

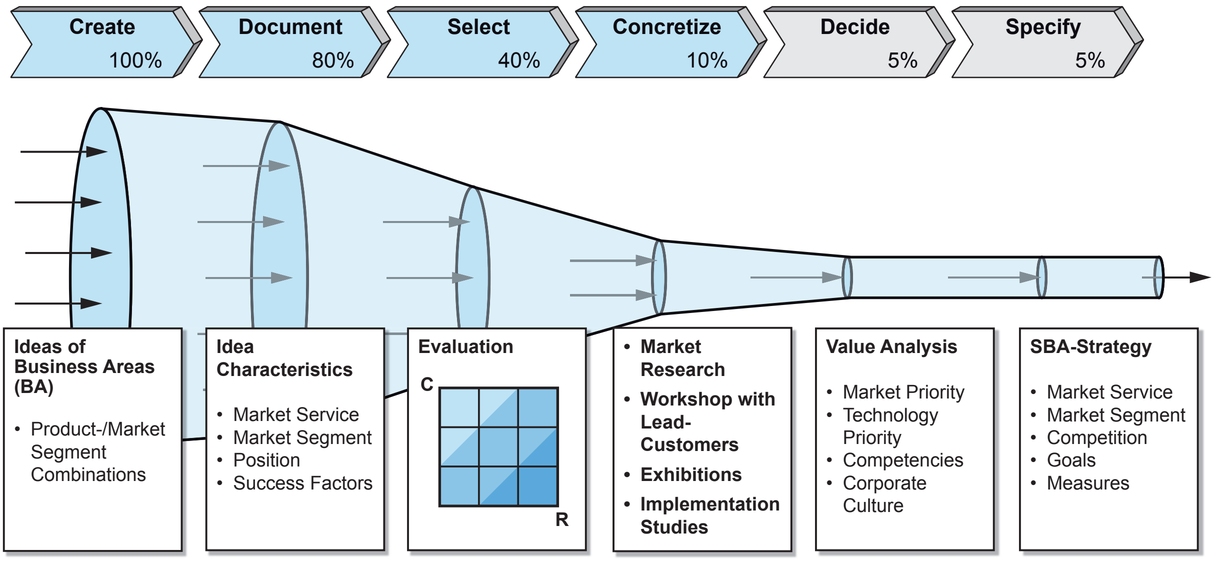
The scenario combination for the electronics industry manufacturing equipment also implies the previously selected scenario for the global environment. The electronics industry manufacturing equipment is characterized by highly integrated production systems enabling individualized production. For being successful in this future, AM-processes and materials have to be qualified for highly integrated production.

2

Future Applications of Direct Manufacturing

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 success potentials identified within the foresight process for the aerospace, automotive and electronics industry. For the systematic generation of ideas and the selection of the most promising ideas, an approach called *Funnel of Idea Selection* was applied. The approach consists of six phases, as shown in figure 2-1.



SBA: Strategic Business Area

Figure 2-1: Funnel of Idea Selection

- **Create:** The first step is the creation of ideas for possible business opportunities. This aims at the identification of conceivable product/market-segment combinations.
- **Document:** In the second step, the identified ideas are documented in idea characteristics. Possible aspects for characterizing the identified ideas are market service, market segments etc.
- **Select:** A selection process is required to make a rough preselection of the identified ideas. Therefore, chances and risks are identified for each idea. According to them, the ideas are positioned in a chances-risks-portfolio. This visualization indicates which ideas should be pursued and which should be rejected.
- **Concretize:** The next step is the concretization of the selected ideas. Market research, workshops with Lead Customers,

visits of trade fairs and implementation studies are suitable approaches for concretizing the most promising ideas.

- **Decide:** By using cost-benefit analyses, a final evaluation of the concretized ideas is conducted. Here, the future market and technology attractiveness of the ideas are assessed; the ideas' compliance with core competencies and conformity with the prevailing corporate culture are further aspects to be considered. Goal of this assessment is the identification of the most promising ideas.
- **Specify:** The most promising ideas are worked out in detail by characterizing the performance, the market segments, competition, goals and measures. The results are clearly structured and documented business unit strategies for the most promising ideas.

Creation, documentation, selection and concretization of ideas for future applications of DM are part of this chapter.

The project focuses the **first four phases of the Funnel of Idea Selection**, as highlighted in pale blue in figure 2-2.

Proceeding in the Project

For each industry, creativity workshops were conducted.

Against the background of the selected reference scenario combinations, (see chapter 1.2) 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 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, product ideas were developed and documented in idea characteristics. Similar ideas are clustered to innovation fields containing concrete product ideas, or just ideas for potential activities in the considered industry.

Subsequently, the identified product ideas/innovation fields from each industry are analyzed in detail to deduce requirements on further developments of AM-technologies. In a following assessment and selection step, the innovation fields are prioritized. First, an assessment regarding chances and risks resulting from market and technology perspective takes place. A higher customer benefit provided through AM and a high market potential are possible chances, as these aspects enhance the attractiveness of a product idea. In contrast, high degree of competition and high investments into research and development represent risks for the realization of an idea.

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.

2.1 Future Applications in the Aerospace Industry

In this chapter, the innovation fields for the aerospace industry are presented. From these innovation fields, the most promising are selected for concretization.

2.1.1 Idea Creation and Documentation

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

For the aircraft production, 37 product ideas were developed. These ideas were clustered to 9 innovation fields:

- Ai1 – Aircraft Interior;
- Ai2 – Multifunctional Structures;
- Ai3 – Energy Saving/Providing Structures;
- Ai4 – Monolithic Structures;
- Ai5 – Morphing Structures;
- Ai6 – Deployable Structures;
- Ai7 – Smart Joinings;
- Ai8 – Out-of-Chamber Manufacturing;
- Ai9 – Manufacturing on Demand.

The following section describes all innovation fields, including an exemplary product idea from each innovation field. The characteristics encompass a short description, a draft, the current technical solution, advantages and disadvantages. A more detailed description of all innovation fields and all developed product ideas are part of the confidential study.

Innovation Field Ai1 – Aircraft Interior

Increasing passenger convenience by individual interior

Aircraft interior increasingly demands for innovative design that concurrently contributes to reduce the total weight of an aircraft and to improve passenger comfort and safety as well as ergonomics in the aircraft. AM and its ability to flexibly process lightweight materials offer a plurality of interesting applications. For instance, interior parts can be designed using lattice structures, combining high strength with a relatively low mass. Thereby, the amount of required material can be minimized [Wor11a].

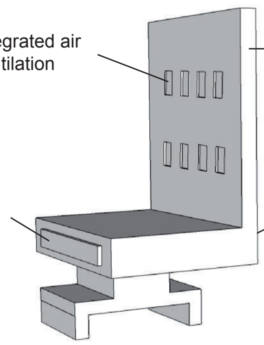
Furthermore, individual or reconfigurable interior becomes possible, such as individually configured, functionally integrated aircraft seats, including self-adjusting mechanisms for automatic adaption to movements. This innovation field also comprises ideas that specifically focus on functional integration of aircraft interior, see also the innovation field *Multifunctional Structures* [Wor11a]. *Seat Frames with Integrated Sub-Systems* is an exemplary idea from this innovation field, see figure 2-2.

Seat Frames with Integrated Sub-Systems

Description

Conventional aircraft seat frames contain a large number of parts made from different materials. The innovative seat frame with integrated sub-systems puts an end to this multipart design. Using AM, monolithic and intelligent seat frames, incorporating electronics, ejection propulsion etc., can be manufactured in a single step. Geometrically adapting seats also feature integrated supports for a higher level of seating comfort and ergonomics, concurrently saving space and housing more passengers. Integrated air channels enable optimal ventilation; electric connection cables can be directly integrated into the seat frame. Due to the one-part design, the amount of connector parts and the total weight can be reduced. New lightweight and functional material could also provide considerable fuel savings which could contribute to improve efficiency and profitability [Wor11a].

Draft



Advantages/Benefits

- Increased rigidity
- Reduced number of parts
- Shorter lead time
- Less opportunity for impact on schedule and price
- Fewer requirements for process and certification controls
- Increased comfort due to customizable/adaptable seats
- Living hinges

Disadvantages/Risks

- Expensive loss if equipment fails during production
- High complexity and high reparation/replacement costs due high functional integration
- Certification for parts is currently not available

Current Technical Solution

Hundreds or thousands of sub-components, produced with subtractive manufacturing methods and mechanical fastening techniques, are assembled to one part.

Type of Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-2: Exemplary idea from the innovation field Aircraft Interior: Seat Frames with Integrated Sub-Systems

Innovation Field Ai2 – Multifunctional Structures

By manufacturing entire aircraft parts additively, *Multifunctional Structures* can be realized in a more efficient way. Parts, which previously required a labor-intensive and expensive assembly in order to be functionally upgraded, can now be produced altogether. Even more, new functions can be included from scratch. For example, traces, active chips and entire sensor systems, including electronic wiring and connectors, can be embedded into one part. Through active sensing of the flight environment for feedback flight control, intelligent structures – in terms of adaptronics or self-optimization and structural health management – become feasible using multifunctional structures [Bar11], [Wor11a]. Through the integration of acoustic and thermal insulation mats into airplane cabin walls and environmental ducting, sound deadening interior panels and frequency modulation structures (heat and sound-absorbing properties) can be realized [BAS07-ol], [Wor11a].

Multifunctional Structures contribute to improve part performance.

Functional integration opens up a huge potential to save costs, as assembly becomes obsolete. Furthermore, multifunctional structures, enabling absorption and storage of energy, can be used to replace batteries [Wor11a]. Ideas that specifically focus on energy functions are part of the innovation field *Energy Saving/Providing Structures*. An exemplary idea for *Multifunctional Structures* is shown in figure 2-3.

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].

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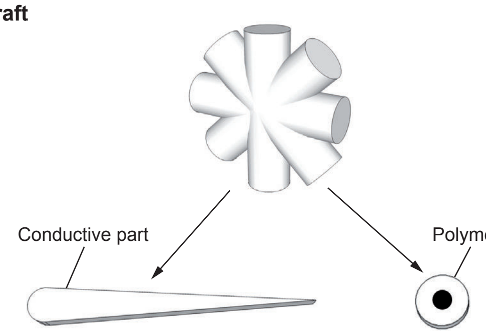

Advantages/Benefits

- 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 assessable
- 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 Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-3: Exemplary idea from the innovation field Multifunctional Structures: Embedded Sensors

Innovation Field Ai3 – Energy Saving/Providing Structures

Intelligent energy concepts contribute to reduce consumption of conventional energy.

Another possible field that bears the opportunity to intelligently apply AM-technologies revolves around the area of *Energy Saving/Providing Structures*. Here, the focus specifically lies on the combination of appropriate AM-design with new materials/material properties. For instance, landing gear or frame parts could act as springs to store kinetic energy and release it while taking-off. Moreover, parts which connect areas of different temperatures in an aircraft could be used as thermoelectric generators to reduce the consumption of conventional energy [Wor11a]. Figure 2-4 shows an exemplary idea from this innovation field.

Smart Energy Consumption Devices

Description

The development of an efficient energy system is one of the major challenges for the development of aircrafts. Smart energy devices, which use additively manufactured structure designs, combining different materials, could promote intelligent consumption and storage of energy, which otherwise would be lost. For instance, during landing a large amount of kinetic energy is produced. Parts, which are able to store energy while landing and releasing it when the input energy is lower than the load energy, would be beneficial [Zul11-ol]. Springs designed for AM enable them to change properties. Tailored energy storages, integrated into parts of a plane where vibrations are emitted, could provide energy for water or cabin heating. By consequently enhancing these techniques, aircrafts can save energy and become more efficient. There are already investigations on systems for energy recovery, such as recovering body heat of the passengers to power the cabin features [Evo10-ol]. The main challenge is to store more energy than its transportation would consume [Wor11a].

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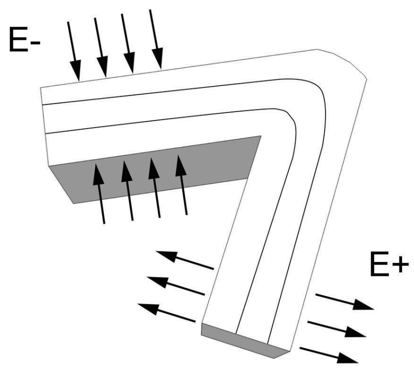

Advantages/Benefits

- Less fuel consumption
- Higher efficiency
- Fewer batteries needed

Disadvantages/Risks

- New principles for storing energy are needed
- Adoption
- Increase in part complexity
- Insufficient capacity

Current Technical Solution

Today, energy storage in aircrafts is still a major challenge.

Type of Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-4: Exemplary idea from the innovation field Energy Saving/Providing Structures: Smart Energy Consumption Devices

Innovation Field Ai4 – Monolithic Structures

Production of parts without joinings

Monolithic Structures are parts that are made from one part and have a 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 reduce production costs as assembly becomes obsolete. In addition, significantly less waste is generated. For instance, in case of airframe components, 90 percent of a block of pricey titanium on the machine shop floor could be leaved up [Dil11-ol].

Increased rigidity and stability of parts due to Monolithic Structures

Even more, the inherent connective points pose a threat to the stability of parts. By manufacturing monolithic structures in one piece by using AM-technologies rigidity and stability of aircraft parts can be improved significantly. Moreover, the weight of parts can be reduced and isolation and wiring can be directly integrated into the part [Wor11a]. An exemplary idea for *Monolithic Structures* is shown in figure 2-5.

Outer Skin

Description

The outer skin of an aircraft is huge and consists of several, more or less similar parts connected with each other. In order to improve stability without increasing component weight, it could be redesigned for its manufacturing by AM-technologies. Manufacturing the outer skin as a monolithic structure would significantly reduce the amount of weak connection spots between the outer skin and the airframe. Combined with a double-walled structure and further intelligent structures, for instance according to the honey-comb principle, an increase of stiffness and wear resistance where it is needed, combined with a decrease in weight could be realized. Furthermore, integrated wiring could contribute to better exploit the available space [Wor11a].

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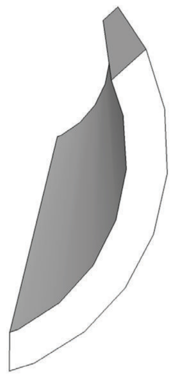

Advantages/Benefits

- Integrated isolation
- Less parts require less assembly
- Less "weak" connection points
- Faster assembly

Disadvantages/Risks

- Decreasing safety, as thinner outer skin may be more dangerous
- Build chamber volume of AM-machines is limited
- Cost-intensive reparation
- Aircraft construction requires materials that can withstand extremely high temperature changes, and are fire resistant

Current Technical Solution

Many components are combined together using mechanical or laser fastening techniques. Intense research is currently made [Evo10-ol].

Type of Ideas

☐ product update ☒ adaption ☐ innovation

Figure 2-5: Exemplary idea from the innovation field Monolithic Structures: Outer Skin

Innovation Field Ai5 – Morphing Structures

Morphing Structures enable parts that are adaptable to environmental conditions.

The ability of AM to produce highly flexible and functionally integrated parts fosters the idea to create “smart” parts that adapt/react in response to the operational environment – the so called *Morphing Structures*. For instance, the cross-sectional shape of a wing with hybrid laminar flow control could adapt to the respective flight phase and thereby, reduce viscous drag [Wei06-ol], [HKF10].

The usage of morphing structures provides many advantages, depending on the field of application. For example, manufacturing of aircraft wings as an adaptive structure allows better aerodynamics compared to conventional wings; they are also better for fast and tight turns. Variable camber can contribute to cope with different weights; affections by gusts of wind can be compensated through fast changes in the airfoil; as the surface curvature can adapt to different high-speed phenomena, fuel consumption can be significantly reduced. Using morphing structures can also significantly contribute to reduce the number of moving parts and the need for wiring which results in decreased weight and assembly effort [Wor11a]. Figure 2-6 shows an exemplary idea from this innovation field.

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].

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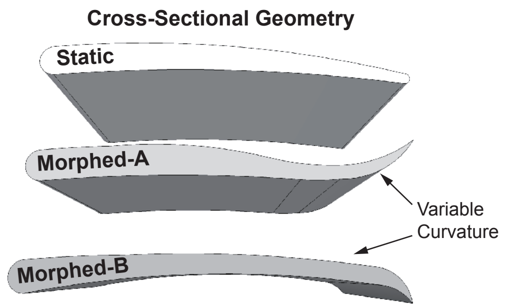

Advantages/Benefits

- 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 Ideas

☐ product update ☐ adaption ☒ innovation

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

Innovation Field Ai6 – Deployable Structures

Production of small-sized, expandable parts

Following the example of the medical industry, which uses expandable stents to broaden coronary vessels, the aerospace industry can benefit from the idea of structural "blow up" – the so called *Deployable Structures*. Aircraft parts can be produced in small sizes; in a subsequent step the part can be expanded to the required part size. Thereby, it is possible to overcome limitations on the build chamber volume.

The unfolding of parts can be realized by a twofold approach: firstly, by a subsequent heat treatment; and secondly, by telescoping structures. In addition, deployable structures can increase the degree of functional integration for conventional parts, and would therefore be a cost effective way to realize ideas provided in the innovation field *Multifunctional Structures* [Wor11a], [AFR10], [MTB+07]. An exemplary idea for *Deployable Structures* is shown in figure 2-7.

Tailored Structures

Description

In contrast to standardized parts produced in bulk production, tailored structures are perfectly adapted to fit for individual purposes, as every part is produced for its stress situation and can therefore be used more efficiently. Compared to conventional subtractive manufacturing technologies, AM's ability for functional-driven design opens up unlimited possibilities to realize tailored, deployable structures in a more cost-efficient way, concurrently providing additional functionality. For instance, strength, stiffness and insulation properties etc. can be improved. Since generally there are no limitations on complexity, small-sized parts of any arbitrary deployable geometry can be manufactured using AM and easily be "mechanically unfold"/deployed to bigger ones in a subsequent step [AFR10]. Thereby, build chamber volume would not set any limitations. This idea can also be combined with lattice structures in order to store energy or air pressure within the structure and to release it for the deployment of the build part [MTB+07], [Wor11a].

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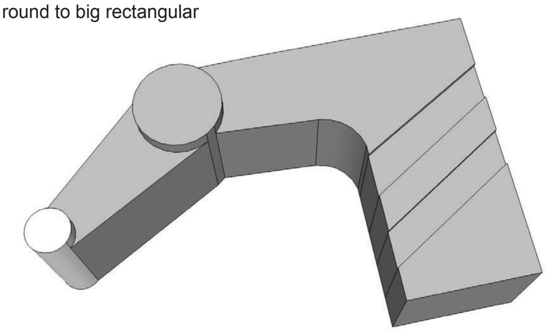
Structural "blow up" from tiny round to big rectangular



Advantages/Benefits

- Limitations on build chamber volume can be overcome
- Multifunctional use
- Customer/application specific parts
- Individual/optimized design leads to higher part efficiency

Disadvantages/Risks

- Simulation and experience needed for each single purpose
- Material availability
- High part complexity

Current Technical Solution

Today's manufacturing technologies render customization extraordinarily expensive. There are several mechanisms for deploying structures, ranging from coronary stents that are used for the extension of arteries to satellite booms and solar arrays [AFR10].

Type of Ideas

☒ product update ☐ adaption ☒ innovation

Figure 2-7: Exemplary idea from the innovation field Deployable Structures: Tailored Structures

Innovation Field Ai7 – Smart Joinings

Intelligent part designs to avoid joinings

Another way of taking advantage of the flexibility provided by AM-technologies is to enhance the design of parts with regard to improved connectivity. So far, aircrafts use a variety of connectors, such as bolts and screws, which weaken the structural integrity and also represent a considerable cost factor. The main idea of this innovation field is a *Smart Joining* mechanism which is directly integrated into part structure, according to the principle of LEGO® building blocks.

Thereby, fasteners can be completely replaced through flexible designs. Besides strengthening the parts and reducing costs, the assembly time would decrease while durability of parts increases. Moreover, this mechanism can contribute to modular customization of parts [Wor11a]. Figure 2-8 shows an exemplary idea from this innovation field.

Integrated Joining Methods

Description

Conventional joining methods like welding, staking, clinching etc. weaken the material structure. Thus, weak spots are often located in the respective areas. Additively manufactured joining mechanisms are directly integrated into the part structure. Thereby, parts are designed to perfectly fit into each other according to the principle how LEGO® parts snap together. Joining methods with flexible and any arbitrary design could eliminate the need for fasteners, and tools for assembly become obsolete. As this joining method requires a huge geometric complexity, realization of that kind of joining will only be affordable if AM-technologies are used [Wor11a].

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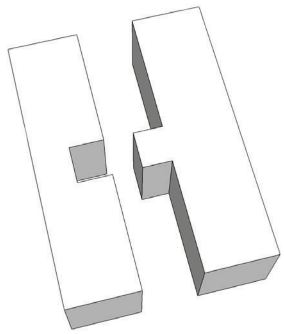

Advantages/Benefits

- Elimination of fasteners
- Higher durability and stability of parts
- Faster assembly
- New (intelligent) mechanisms possible

Disadvantages/Risks

- Modeling/QC design
- High reparation costs
- New control technologies needed
- High part complexity
- High accuracy and surface quality required

Current Technical Solution

Currently, many different components are assembled and joined by fasteners to one part.

Type of Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-8: Exemplary idea from the innovation field Smart Joinings: Integrated Joining Methods

Innovation Field Ai8 – Out-of-Chamber Manufacturing

Overcoming build size limitations by Out-of-Chamber Manufacturing

This group of ideas emerges from the demand for manufacturing large parts with AM-technologies. In order to profit from the advantages of AM-technologies extensively, especially in the aerospace industry, it will be important to provide AM-machines with larger build chambers. The vision of this innovation field is a completely innovative manufacturing mechanism, combining single AM-machines/AM-robots to an integrated *Out-of-Chamber Manufacturing* system in a scalable and modular way adapted to the current purpose. Thereby, it is possible to overcome existing build chamber limits, as parts can be manufactured everywhere without a fixed space: several robots can manufacture parts concurrently and in a very flexible way.

Out-of-Chamber Manufacturing can expand the range of the application of AM. For instance, such AM-robots can be applied for structure repair, even directly on-site [Wor11a]. An exemplary idea for *Out-of-Chamber Manufacturing* is shown in figure 2-9.

Scalable Modular Manufacturing Systems

Description

Today, the AM-machines are characterized by low build up rates and a low build chamber volume. Therefore, AM is still limited to low-scale production of small build-sized parts. A scalable modular manufacturing system, consisting of multiple, independent machines that act as modular robots, can contribute to overcome these limitations. These manufacturing systems are modularly scalable and the number and the arrangement of machines/robots can be adapted to practically any purpose, production-flow model and factory layout. The more machines are involved, the faster the production process is finished. Due to the high flexibility of the modular manufacturing system, localized production is possible. For instance, the modular manufacturing systems can also be applied for on-site part reparation [Wor11a].

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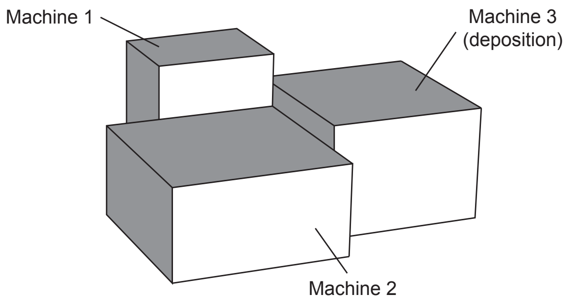

Advantages/Benefits

- Build chamber volume doesn't set any limitation on part size
- Multiple materials could be joined together
- Manufacturing times can be reduced
- New applications for AM-technologies become possible
- Application of on-site reparation

Disadvantages/Risks

- Robotics and communication controls are needed
- Accuracy
- Cost-intensive equipment
- Quality of repair

Current Technical Solution

Currently, AM-technologies are limited to a rather small build size. Therefore, huge AM parts can only be produced by assembling a large number of single smaller parts.

Type of Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-9: Exemplary idea from the innovation field Out-of-Chamber Manufacturing: Scalable Modular Manufacturing Systems

Innovation Field Ai9 – Manufacturing on Demand

Taking advantage of AM's flexibility to produce parts "just in time" without tooling

The flexibility of AM-technologies can also provide benefit for *Manufacturing on Demand*. Due to the high adaptability and flexibility of AM-machines, no tooling is needed. Thereby, storage costs can be reduced significantly, and furthermore on-demand-production fosters the intactness of parts because no damaging can occur during storing. Additionally, spare parts can be adapted and improved continuously if any malfunctions of the original parts have already occurred.

Manufacturing on demand is especially interesting for on-site manufacturing: any metal part of aircraft, except fuselage, can be printed just-in-time, based on scanning the damaged part. Furthermore, ideas from the innovation fields *Multifunctional Structures* and *Energy Saving/Providing Structures*, enabling absorption and storage of energy, can be combined batteries that can be manufactured on demand [Wor11a], [Fra10-ol]. An exemplary idea for *Manufacturing on Demand* is shown in figure 2-10.

On Demand Spares/Preventive Maintenance (PM) Parts

Description

In order to provide a highly efficient product, short down-times are essential. Therefore, a fast availability of spare parts needs to be guaranteed which requires part storage and in turn leads to high storage costs. In addition, conventional manufacturing technologies are cost-intensive for manufacturing parts on-demand which applies to low-scale production or manufacturing out-of-production parts [Fra10-ol]. Using AM-technologies, parts can be produced on-demand. Building-up inventories of new and spare parts as well as expensive tooling and dies become obsolete. Moreover, logistic costs can be reduced, as there is no need for centralized production and storage anymore. All in all, part acquisition time can immensely be reduced [Wor11a].

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Advantages/Benefits

- Reduction of time and costs for maintenance
- Pre-planned maintenance is feasible: part is printed before aircraft arrives
- Less transportation, packaging and storage

Disadvantages/Risks

- Costly start-up
- Maintenance and availability of machines/manufacturing equipment
- Quality control of parts
- Process control
- Further production capacity is needed

Current Technical Solution

Lengthy and costly procurement processes hinder quick maintenance. Huge inventory stocks are built-up to guarantee availability of spare parts.

Type of Ideas

☒ product update ☒ adaption ☐ innovation

Figure 2-10: Exemplary idea from the innovation field Manufacturing on Demand: On Demand Spares/Preventive Maintenance (PM) Parts

2.1.2 Idea Selection

Obviously, the innovation fields considerably differ in their attractiveness for the application of AM-technologies. Some product ideas can be realized simply with minimal 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.

Based on this, each innovation field can be positioned in a chances-risks-portfolio, as shown in figure 2-11. For the innovation fields, the ordinate intercept shows the chances; the abscissa intercept indicates the risks.

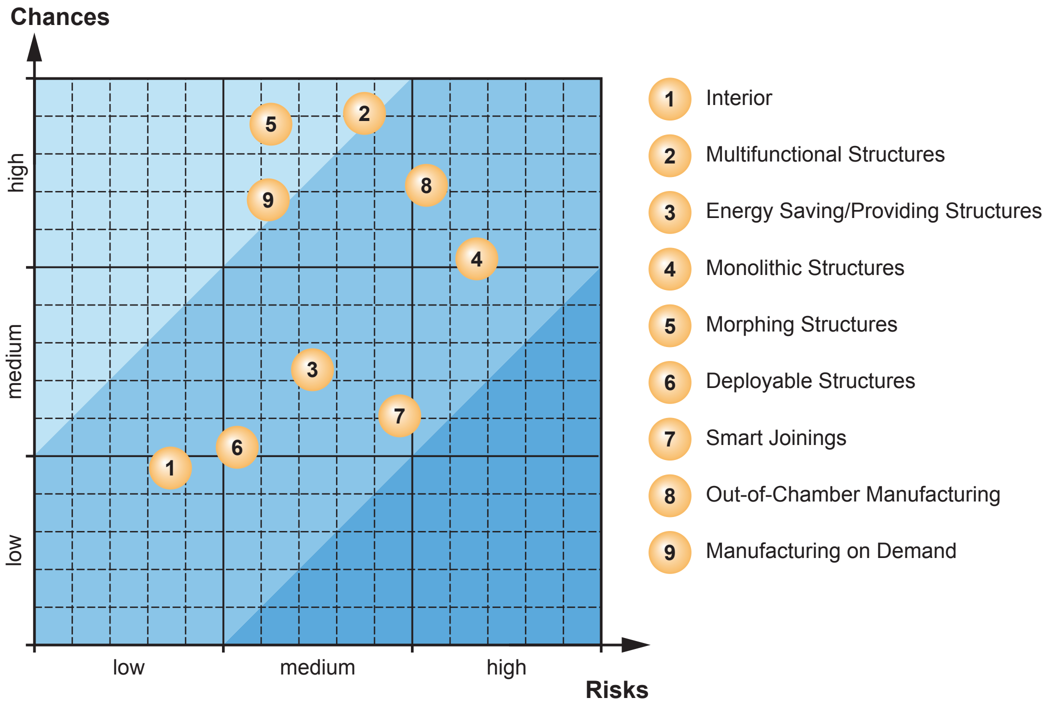


Figure 2-11: Prioritizing innovation fields of the aerospace industry using a chances-risks-portfolio

Morphing Structures and Multifunctional Structures were selected as the most promising innovation fields in the aerospace industry.

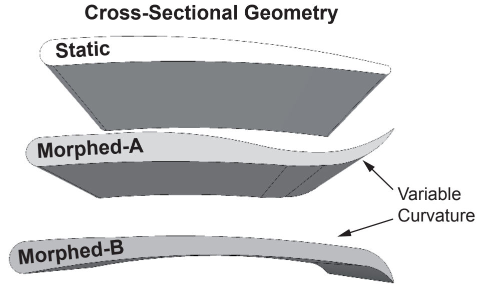
The closer an innovation field is to the top left corner, the higher the attractiveness of the innovation field for the application of DM. The innovation fields *Morphing Structures* and *Multifunctional Structures* were highly prioritized, as they offer the greatest potential for the application of DM. According to the experts' assessment, *Monolithic Structures* entail major risks. The innovation field *Aircraft Interior* involves the lowest risks, but concurrently the potential for a wide application of DM is estimated to be low.

2.1.3 Idea Concretization

The highly prioritized innovation fields – *Morphing Structures* and *Multifunctional Structures* were concretized in more detailed characteristics. The concretization includes aspects, such as a detailed description of the innovation field, and specifies the opportunities and barriers that arise from the application of AM-technologies. It also outlines the technical feasibility and the advantages in comparison to the application of conventional technologies. Figure 2-12 visualizes the concretized innovation field *Morphing Structures*. All concretized innovation fields are part of the confidential study.

Morphing Structures

Market Performance

Description of the market service • Product business • Position in the value chain • Unique selling points	Parts with morphing structures are able to quickly change and adapt their shape to different conditions. The change in shape is realized by a complexly designed structure and can be controlled by actuators. Due to their high adaptability, these parts can cover a wider range of tasks compared to conventional parts. "Morphing structures" is a familiar concept: variable sweep, retractable landing gear, retractable flaps and slats, and variable incidence noses are some examples where morphing structures already provide benefit. In addition, nearly all aircraft wings are equipped with such components. Folding, telescoping etc. are applied methods for changing configuration [Wei06-ol]. However, such structures only can realize discrete, mechanical, and rigid configuration states. This innovation field explicitly describes parts with morphing structures that are capable to realize continuous configuration of shape which may become feasible due to new and smart materials and the almost unlimited possibilities of AM. Particularly, changing wing surfaces and controlled airfoil camber entail great potential for applying morphing structures [Wor11a].
Technological product concept • Product structure • Key design features • Hint of possible variants • Substantial performance data (specification)	Morphing structures are designed as one part that is adaptable in its geometry/shape. Instead of changing the position of a static part by using actuators, the part geometry itself can be transformed to a certain level to enable specific functions/properties in order to better manage the current situation. This often implies conflicting requirements, e.g. a reduction of landing/take off times of an aircraft requires flaps which appear on wings to increase area/lift coefficient at low speed; this results in increasing weight the additional flaps add to the aircraft. Using AM, geometrically complex structures may contribute to overcome such conflicting requirements of individual flight conditions. Continuous shape changing does not only require appropriate structures but also advanced skin materials, such as shape memory polymers that can easily reshape and may provide surface smoothness for aerodynamic efficiency when the wing changes its shape in-flight. Concurrently, these materials have to keep structural integrity under compression, tension, bending and flight loads. Even more, the realization of morphing structures depends on many aspects, such as sensors to measure the system's state; control systems to convert the measurements into an activation signal; actuation mechanisms to provide mechanical motion and precise configuration; and efficient power sources to drive actuation. Geometrically flexible structures can contribute to activate shape changes by using aeroelastic energy from the airstream [Wei06-ol], [Wor11a]. **Draft** 
Description of goods and services How will the product be manufactured?	Today, any of the existing conventional, subtractive technologies, which create parts by subtracting material from a work piece, can be applied to engineer morphing structures as described above. As highly complex shapes have to be realized, the structure has to be produced additively. Depending on its purpose of use, the applied materials will differ and therefore different AM-processes will be required.

Technology Performance

Description of customer benefits Advantages and chances of additive manufacturing production	Morphing structures provide a lot of advantages depending on the field of application. For example, manufacturing of aircraft wings as an adaptive structure allows better aerodynamics compared to conventional wings; they are also better for fast and tight turns. Variable camber can contribute to cope with different weights; affections by gusts of wind can be compensated through fast changes in the airfoil; the surface curvature can adapt to different high-speed phenomena and thereby, fuel consumption can significantly be reduced. Morphing structures can also contribute to reduce the number of moving parts and the need for wiring which results in decreased weight [Wor11a].
Description of risks along the value chain Disadvantages und risks for the customers and OEMs	Due to the complex geometry of morphing structures, the long-term durability of these structures can only be guaranteed when all mechanical components are always well oiled. The high complexity of morphing structures can only be realized by AM-processes, which results in high fix costs for broken parts. When morphing structures are used in wings, emergency flight properties must be ensured [Wor11a].

Competition

Conventional manufacturing technologies • What manufacturing technologies are used so far? • What are the benefits of the conventional technologies?	As the geometry of morphing parts is very complex, it is unlikely that conventional manufacturing technologies will be used to produce morphing structures. Current technical solutions for wings are movable control surfaces. The material used for these parts is static. In order to be adaptable, the part consists of many different moving components which can be controlled by actuators. To produce these components, many different manufacturing processes, like milling, casting, etc. are used. Each process on its own is simple and fast, but the high number of components increases the part complexity and requires a complex assembly process [Wor11a].

		lower		comparable		higher
Production costs using AM-technologies compared to conventional technologies	**Production Costs**	[ ]	[ ]	[X]	[ ]	[ ]

		low		medium		high
Added value through using AM-technologies compared to conventional technologies	**Benefit**	[ ]	[ ]	[X]	[ ]	[ ]

Research Approaches

- Which kind of innovations do already exist in this field of innovation?
- What are important research steps that have to be taken to realize future production (future requirements)?

Following the principle of bionics as a model for technological solutions, scientists study highly efficient birds that are capable to significantly increase their performance in the air by the versatile shape of their wings. Numerous scientists have recognized these benefits and take this idea from nature to transfer it to technological inventions. This makes morphing structures the next big thing in aircraft engineering. For instance, NASA already uses morphing structures for a revolutionary „morphing wing" aircraft. Inter alia, morphing structures are applied for so-called micro-aircrafts that have varying wing shapes. Imitating a bird and equipped with cameras and sensors, they are applied for surveillance and espionage [Sci07-ol]. Mimicking bird wings' movements contribute to improve the maneuverability of unmanned aerial vehicles (UAVs) [Sci11-ol].

Ability of DM-technologies

- Is the necessary know-how for applying AM-technologies available?
- Where are the deficits?

	available		partly available		not available
Development	[X]	[ ]	[ ]	[ ]	[ ]
Production	[ ]	[ ]	[X]	[ ]	[ ]
Quality Assurance	[ ]	[ ]	[ ]	[ ]	[X]

Assessment of the Innovation Field

- How do you assess the innovation field?

	very low		medium		very high
Technology Risk	[ ]	[ ]	[X]	[ ]	[ ]
Market Potential	[ ]	[ ]	[ ]	[X]	[ ]
Maturity Level	[ ]	[X]	[ ]	[ ]	[ ]
Competitive Intensity	[X]	[ ]	[ ]	[ ]	[ ]

Reference to other Innovation Fields

- Are there any references to other innovation fields?

Innovation fields such as *Multifunctional Structures*, *Monolilthic Structures* and *Deployable Structures* can be used as compliant mechanisms for morphing structures [Wor11a]. Another mechanism resulting from bionics is based on cellular structures, such as foams, honeycombs, and lattices. They are composed of unit cells, and are characterized by high strength and their relatively low mass. Due to that and under affection by force, motion, or energy, cellular structure is capable to change its shape. In analogy from nature, this mechanism can be transferred to realize morphing structures [CSS09-ol], [JWR+06-ol].

	give up	put back	pursue	realize
Conclusion	[ ]	[ ]	[X]	[ ]

Figure 2-12: Detailed characteristics for the innovation field Morphing Structures

In the aerospace industry, innovations revolve around a broad variety of aircraft parts. Most importantly, additively manufactured goods can significantly contribute to increase efficiency of aircrafts. Additionally, passenger convenience and the availability of spare parts can respectively be improved and provided.

2.2 Future Applications in the Automotive Industry

This chapter provides an overview for the innovation fields developed for the automotive industry. From these innovation fields, the most promising are selected for concretization.

2.2.1 Idea Creation and Documentation

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

Using the reference future scenario as an impulse, 33 product ideas have been developed for the automotive production. These ideas were clustered to 8 innovation fields:

- Au1 – Functional Body-in-White;
- Au2 – Individualized Interior;
- Au3 – Optimized Tooling;
- Au4 – Handling of Fluids;
- Au5 – Parts on Demand;
- Au6 – Optimized Power Train;
- Au7 – Electric Drive;
- Au8 – Functional Material/Multi-Material.

The following section provides short descriptions of all innovation fields, including an exemplary product idea from each innovation field. The characteristics encompass a short description, a draft, the current technical solution, advantages and disadvantages. More detailed descriptions of all innovation fields and all developed product ideas are part of the confidential study.

Innovation Field Au1 – Functional Body-in-White

Holistic functional integration into the Body-in-White.

Following the trend of functional integration, the automotive industry offers a broad variety of possible applications. The range of applications in the innovation field *Functional Body-in-White* reaches from channels/fluid conduits integrated into the body panel to customizable (tuning, structural color etc.), and safety-increased structural parts. Integrated channels can contribute to improve body stiffness and stability of parts [Red11-ol].

Especially, the omnipresent discussion on reduction of fuel consumption promotes less weight, less parts and less assembly. Functional integration represents a cost effective way to produce parts for functional body-in-white, combining different functions in one piece. Thereby, fastening elements become obsolete, relative motions of parts can be eliminated, and the number of parts as well as part weight can be reduced significantly [Wor11b]. An exemplary idea for *Functional Body-in-White* is shown in figure 2-13.

Automotive Doors

Description

Due to the high flexibility of AM-technologies, customization of automotive parts becomes less costly compared to manufacturing these parts with conventional technologies. Using AM, customizable door designs can be manufactured with individual geometries, such as geometrically different window frames. Moreover, automotive doors entail a great potential for functional integration, for instance functional compartments, speaker architectures, easy to handle window regulators, air ducts, airbag holders and crash boxes can be directly integrated in the door structure. Ameliorated and highly integrated door structures can furthermore enable space-efficient design. In addition, doors significantly contribute to increasing the passengers' safety in case of a lateral impact. Using AM, lattice structures or honey-comb structures offer great potential for manufacturing doors that are compliant in certain areas and stiff in other areas [Red11-ol]. This in turn increases safety and concurrently reduces the weight of the automotive as well as vibrations and noise [Wor11b].

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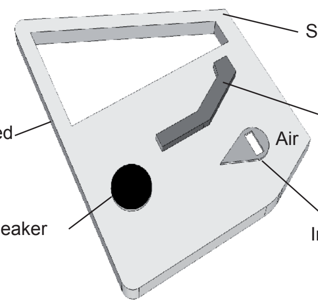

Advantages/Benefits

- Customizable parts
- Increased safety
- Fewer parts are required
- Sources of error can be reduced

Disadvantages/Risks

- Multi-material problems
- Part size is limited to build chamber volume
- Repair of functional integrated parts is more difficult
- Higher costs possible

Current Technical Solution

Today, customization of doors is relatively unusual.

Type of Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-13: Exemplary idea from the innovation field Functional Body-in-White: Automotive Doors

Innovation Field Au2 – Individualized Interior

Increasing customer satisfaction by adaption of interior components.

The immense flexibility of AM-technologies fosters *Individualized Interior* in automotives. Since customers tend to have special demands for their cars, the possibility to offer highly customized cars is a unique selling point. For instance, the principle "freedom of design" enables the creation of improved handling configurations for switches, pedals or entire dashboards which are configurable to meet the individual specifications. Especially, comfort, passive safety and medical criteria put requirements on the seat that has to guarantee proper conditions for the human body.

AM can provide benefit in this instance; before manufacturing the seats, the driver could be scanned in order to manufacture the seat according to the individual stature. Even more, following the idea of functional integration, self-optimizing mechanisms can be integrated in the seat [Wor11b]. Figure 2-14 shows an exemplary idea from this innovation field.

Driver Interaction – Steering Wheel

Description

Comfort and aesthetics of automotive interior are highly important for the customers. By exploiting the freedom of design, AM offers great potentials to manufacture unique interior goods and interior designs that are highly adaptable to individual purposes. Such complex one-piece designs cannot be produced by conventional manufacturing methods. Highly customizable steering wheels featuring various in-site geometries and individually configurable controls can be realized by AM. Furthermore, a heating and cooling system, an integrated hydraulic system unit as well as active feedbacks can be implemented into the design [GFB+11-ol]. Directly integrated active safety systems, such as airbags, as well as passive safety systems (big crumple zone through complex energy absorbing design/structure) can contribute to increase passenger safety [Wor11b].

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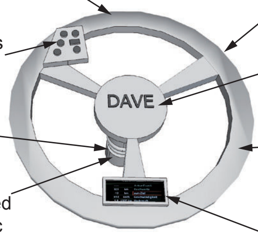

Advantages/Benefits

- Better ergonomics
- Increased safety
- High perceived value
- Possibility of economic production of customized or limited edition steering wheels
- High differentiation potential
- Design to fit needs
- Mass customization

Disadvantages/Risks

- Multi-material issues
- Over-customization
- Complex ordering and design processes
- Adaption is costly
- Repair costs complexity
- Lower resale value of automotives

Current Technical Solution

Today, customization of steering wheels is not possible; just a few different variants in terms of size and surface material can be ordered.

Type of Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-14: Exemplary idea from the innovation field Individualized Interior: Driver Interaction – Steering Wheel

Innovation Field Au3 – Optimized Tooling

Enhancing the design of tools

The innovation field *Optimized Tooling* focuses on the integration of cooling channels into tooling parts. So far, the cooling channels are drilled into the mold. This technology only supports straight and rather simply designed cooling channels which can cause uneven temperature levels on the cavity surface as well as uneven cool-down processes. Cooling highly stressed surfaces is not always feasible. Moreover, drilling processes have certain risks: For deep holes, there is always the danger of ejector holes, or of breakage of the drill. Thereby, the tooling/mold may be damaged and become unusable [May09-ol].

By applying AM-technologies in this sector, a more flexible way of arranging cooling channels can be achieved and the cross-section of the cooling channel can take any shape. This optimized tooling could enable uniform heat dissipation, quicker cooling processes as well as higher durability of parts. Thereby, both the (surface) quality and economics of injection moulded parts (cost efficiency) can be improved [May09-ol], [Wor11b], [NDS+04-ol]. An exemplary idea for *Optimized Tooling* is shown in figure 2-15.

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 manufactured 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].

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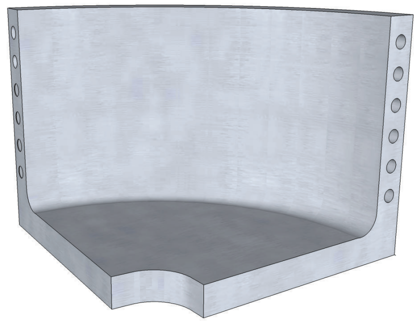

Advantages/Benefits

- 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 the 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 channles that are used to produce millions of parts in injection moulding operations or many thousand metal parts in die casting [May09-ol].

Type of Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-15: Exemplary idea from the innovation field Optimized Tooling: Tooling with Integrated Channels

Innovation Field Au4 – Handling of Fluids

New design possibilities due to flexible production

By taking advantage of the infinite geometry possibilities imposed by AM-technologies, it is possible to improve the *Handling of Fluids.* Pipes, valves, restrictors etc. could be geometrically adapted to their individual purpose. For instance, the geometry of heat exchangers could be adapted to an optimal exchange of thermal energy. Through capillary channels, the fluid is led to the surface where it is needed. Due to constant outer wall thickness, uniform heat transfer and gas distribution can be guaranteed [May09-ol].

By applying AM in this area, efficiency can be increased significantly. Moreover due to the lattice inner structure of the part, weight and volume of those parts can be reduced while part stability can be increased [TCT10-ol], [Wor11b]. Figure 2-16 shows an exemplary idea from this innovation field.

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, lowering the weight of the product 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, due to reduced product 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].

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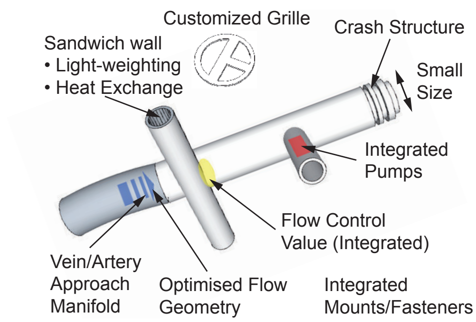


Advantages/Benefits

- 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 Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-16: Exemplary idea from the innovation field Handling of Fluids: HVAC (Air-Conditioning)

Innovation Field Au5 – Parts on Demand

Manufacturing spare part on demand reduces storage.

This innovation field encompasses product ideas for *Parts on Demand*. Especially in the automotive industry, the scale of storing spare parts is extraordinarily huge. Improvements in this sector bear an immense opportunity to save costs, especially as tooling for special spare parts is even more expensive. AM offers the potential to drive down the degree of storing to a large extent, as parts that are required can be produced just-in-time and directly on-site. Costs for tooling can be cut entirely as tooling becomes obsolete [Wor11b]. An exemplary idea for *Parts on Demand* is shown in figure 2-17.

Spare Parts on Demand

Description

Today, cars consist of thousands of different parts. In order to keep the customer satisfaction high, a fast availability of spare parts needs to be guaranteed, even if the car is not part of the OEM's portfolio anymore. Therefore, a high amount of different parts have either to be held in stock for a long time or special tools have to be produced which drastically either increases the storage or the tooling costs. Even more, if a tool is not available anymore, the part can be scanned and directly manufactured. Using AM-technologies for on demand production of spare parts can contribute to reduce the storage costs, concurrently keeping the availability time of spare parts minimal. The need to store expensive production tools may drop to zero, as AM replaces tooling [Wor11b].

Draft

Advantages/Benefits

- Expensive tool production becomes obsolete
- Expensive stocking of parts can be reduced
- Small lot sizes

Disadvantages/Risks

- Missing approvals
- Form is fixed
- Part size is limited to the build chamber volume

Current Technical Solution

Currently, spare parts are produced for stock.

Type of Ideas

☒ product update ☐ adaption ☐ innovation

Figure 2-17: Exemplary idea from the innovation field Parts on Demand: Spare Parts on Demand

Innovation Field Au6 – Optimized Power Train

AM is a key technology to meet demands for ecologically friendly solutions.

In future, the automotive industry will come up with a number of different *Optimized Power Train* concepts such as fuel cell, gas, etc. due to the increasing environmental awareness in society. Furthermore, individuality will also impose requirements on the automotive production. As a consequence, diversity of parts is increasing. AM is an appropriate technology to cope with these flexible demands.

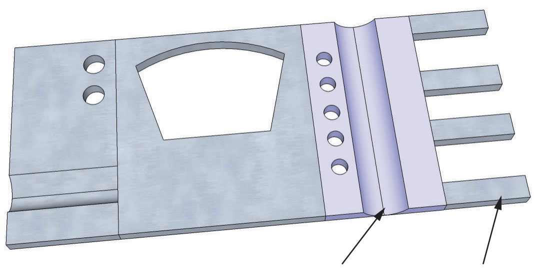
Additionally, AM opens up possibilities for weight and size reduction of power train parts. Single elements and functions can be integrated into the structure, directly where needed. For instance, using integrated channels (fuel, cooling, electric etc.) for injectors of motors thermodynamic characteristics can be improved and fuel consumption can be reduced. Even more, longer durability of parts can be achieved. Even, individual motorization and configuration of the power train, including an adaption to the profile of the driver become possible applications for AM. Regional facts, for instance climate characteristics, can also be taken into account while designing/manufacturing the power train [Wor11b]. Figure 2-18 shows an exemplary idea from this innovation field.

Complete Engine Block

Description

Using conventional subtractive manufacturing technologies, the production of an entire engine block in one part is not possible. Here, the application of AM-technologies offers new opportunities: a complete, functionally integrated engine block could be manufactured in a single step, for instance with cooling channels, electrical connection cables and further sensors directly integrated into the structure. Air-gap insulation between hot parts can be realized as well as double wall motor coatings. Furthermore, an optimized exhaust circulation can lead to higher efficiency. Due to the monolithic manufacturing in a one-step process, no further assembly is needed: the whole motor can be mounted inside the car. In addition, using AM, honey-comb structures that are compliant in certain areas and stiff in other areas could contribute to weight reduction which in turn may provide improved fuel savings, emission's rates and engine life [Wor11b].

Draft



Advantages/Benefits

- Better motor management, higher efficiency, lower consumption of fuel
- Shorter assembly
- Integration of functions
- Inner cooling channels
- Freedom of design
- Weight reduction

Disadvantages/Risks

- High complexity of the motor block
- Failure of one part may lead to failure of the whole system
- Repair is difficult
- Build chamber volume sets limits to the part size

Current Technical Solution

Today, many sub-components are produced with subtractive manufacturing methods and mechanical fastening techniques and are assembled to one part. AM-technologies are rarely used for complex engine structures.

Type of Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-18: Exemplary idea from the innovation field Optimized Power Train: Complete Engine Block

Innovation Field Au7 – Electric Drive

The reduction of weight also plays an important role with regard to the *Electric Drive*. So far, especially rechargeable batteries are heavy, and negatively influence the driving dynamics and efficiency of electric cars. Furthermore, battery electric vehicles differ greatly in the design of the power train or the energy storage. Compared to ordinary gasoline powered cars, where aggregates like the heater can be fired by the heat of the combustion engine, the successful implementation of electric cars will also depend on the redevelopment of a multitude of different parts [Wor11b].

Increased functionality of electric drives through AM

With electric cars being on the raise, it is more suitable to implement new manufacturing technologies in this early stage of the development than to intervene in established production processes. Here, the exhaustion of the freedom of design provided by AM might generate new aggregates, featuring advanced functionality. In addition AM can excel at functionality embedded into parts which furthermore could contribute to weight reduction [Wor11b]. An exemplary idea from this innovation field is shown in figure 2-19.

Application in Electrically Powered Cars

Description

Electrically powered cars are going to gain importance in the next decades. Especially for these cars, light-weight design is crucially important. Multi-material parts with complex geometry will be needed to achieve optimal results. As the powertrain of an electrical car completely differs from drivetrains of conventional cars, a lot of new parts will be required. The mass-scale production of new parts for electrically powered cars could represent an incentive for the implementation of new production technologies.

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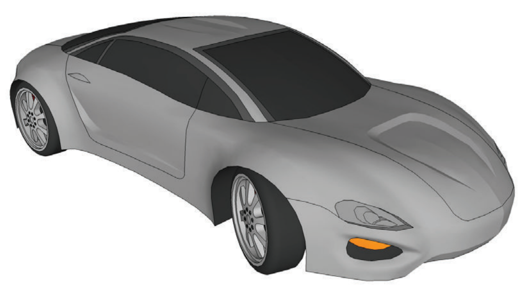


Advantages/Benefits

- Weight reduction
- Multi-material design
- Complex geometries can be realized easily
- New area of application is suitable for new technologies

Disadvantages/Risks

- Mass production requires high lot sizes

Current Technical Solution

Today, parts for applications in electrically powered cars are mainly manufactured using common subtractive manufacturing techniques.

Type of Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-19: Exemplary idea from the innovation field Electric Drive: Application in Electrically Powered Cars

Innovation Field Au8 – Functional Material/Multi-Material

Multi-material processing to enable functional materials

Another promising innovation field follows the principle of *Functional Material (Au8.1)* and *Multi-Material (Au8.2)*. This encompasses two categories: totally new functional materials and existing material with incrementally improved functionality. The core purpose of applying such materials in a part is to enable additional electrical and mechanical properties. Through integration of functionality into materials – for instance electrical or thermal conductivity, self-healing properties – or the combination of tough metals with heat-resistant ceramics, AM can nearly open up unlimited possibilities for automotive applications [Wor11b].

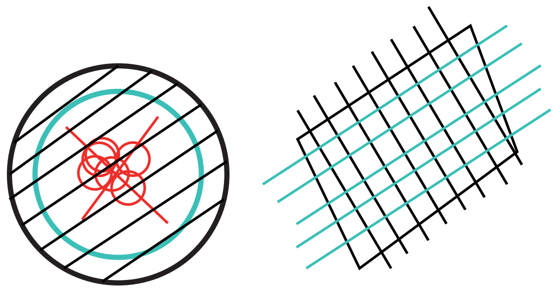
Functional materials combined with functional integration can even enable new electrical and mechanical functions in automotives. For instance, shape-memory alloys can contribute to adaption and self-optimization in automotive applications. In addition, AM-technologies can contribute to increase efficiency and the strength of parts. In particular, AM can meet increasing local requirements which also gave birth to the innovation field *Optimized Power Train* [Wor11b]. Figure 2-20 shows an exemplary idea from this innovation field.

High-Tech Materials/Material Modification

Description

In order to fulfill the customers demand for more individuality, the variety of products is rising. Due to high-tech materials processed with AM-technologies, the individualization of cars can be shifted to a higher level. Instead solely adapting colors and equipment of a car, materials can be adapted as well with regard to material properties that could be modified and adapted to individual purposes such as different climate regions. For instance, multi-material combinations of metal and ceramics could be used to make electronics of cars produced for regions with hot climate. Thereby, part properties and part life times could be ameliorated significantly. In addition, high-tech materials could provide new functionality which could be beneficial in many instances, i.e. materials with high thermal conductivity can be applied to optimize heat exchange [NMG+11], [May09-ol], [Wor11b].

Draft



Advantages/Benefits

- Adaption of parts for individual conditions
- Adapted products might last longer
- Higher functionality provided by high-tech materials with new properties opens up new possibilities for applications

Disadvantages/Risks

- High lot sizes production is challenging
- Increased product and design complexity due to higher product variety
- Further logistical costs

Current Technical Solution

Equipment and colors of automotive parts can be adapted; Materials frequently remain unchanged.

Type of Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-20: Exemplary idea from the innovation field Functional Material/Multi-Material: High-Tech Materials/Material Modification

2.2.2 Idea Selection

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/ product 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 2-21. For the innovation fields, the ordinate intercept shows the chances; the abscissa intercept indicates the risks.

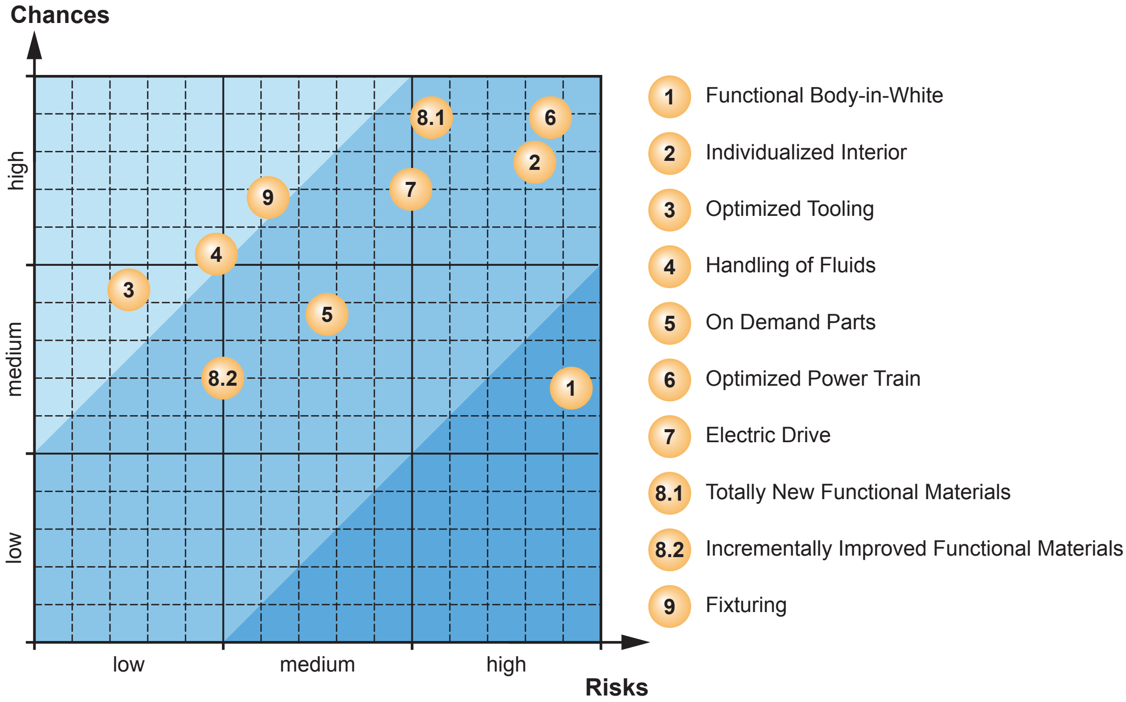


Figure 2-21: Prioritizing innovation fields of the automotive industry using a chances-risks-portfolio

Handling of Fluids and Optimized Tooling were selected as the most promising innovation fields in the automotive industry.

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 evaluation of the innovation fields shows that the innovation fields *Handling of Fluids* and *Optimized Tooling* are classified as the most promising for the application of DM. The innovation fields *Optimized Power Train* and *Totally New Functional Materials* have a significantly higher potential with regard to DM, but they also have considerably higher risks. According to the experts' assessment, the innovation field *Functional Body-in-White* has the lowest potential for applying AM-technologies in the automotive industry.

2.2.3 Idea Concretization

The highly prioritized innovation fields – *Handling of Fluids* and *Optimized Tooling* – were concretized in more detailed characteristics. The concretization includes aspects, such as a detailed description of the innovation field, and specifies the opportunities and barriers for the application of AM. It also outlines the technical feasibility and the advantages in comparison to the application of conventional technologies. Figure 2-22 visualizes the concretized innovation field *Handling of Fluids*. All concretized innovation fields are part of the confidential study.

Handling of Fluids

Market Performance

Description of the market service • Product business • Position in the value chain • Unique selling points	In automotives, fluids are often used for heat exchanging processes. The intelligent and efficient handling of fluids is important in order to optimize the performance of the product, especially in the motor sports sector. Depending on the application, these parts have to be optimized for performance, critical strength properties and weight as well as space reduction [Wit10-ol]. Applying AM-technologies, for instance, parts for air conditioning systems or heat exchangers with highly integrated functions and individualized geometries can be manufactured as monolithic structures in a single step, reducing the number of components whereby parts become less prone to leakage and assembly can be eliminated. Higher efficiency of these components can further be realized by intricate, optimized lattice structures, varying thickness skins or walls designed in sandwich structures. The rejected heat of the air condition and the generated coldness can be used for further heat or cool processes. The individually adapted part geometry can raise the crash resistance. In general, AM excels at the possibility for integrating conformal channeling systems into parts, no matter which fluid they are taken for [HHD06].
Technological product concept • Product structure • Key design features • Hint of possible variants • Substantial performance data (specification)	Highly integrated air conditioning systems are designed to specially fit one car configuration, therefore mass customization will be needed. These systems feature a reduced volume and a decreased weight, and enable optimized cool or heat processes. Thus, they are more efficient than previous generations. In practice, there are already approaches for additively manufactured heat exchangers that are optimized for internal and external performance. For example, struts are directly integrated in the structure of heat exchangers in order to increase internal surface (high surface-volume ratio). Even more, the flow of the cooled fluid can be disrupted to improve heat transfer. Comparably complex designs with integrated cooling fins are being used for the outside form to maximize the cooling surface area and the work done by the cooling air, as it passes through the device. This, in turn, ensures a maximum of heat exchange. Manufacturing such parts requires materials with properties such as corrosion resistance, strength and heat conduction (high thermal conductivity) [NMG+11].
Description of goods and services How will the product be manufactured?	Due to geometrically and structurally high complexity, these parts cannot be manufactured by subtractive manufacturing technologies. Practical approaches already demonstrate the superiority of AM-technologies for manufacturing parts for handling of fluids. As materials needed for producing those parts may differ depending on the individual purpose, different AM-processes can be applied.

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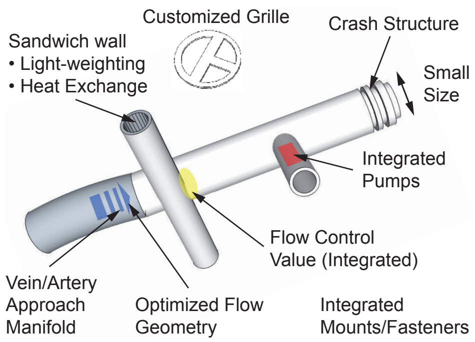

Technology Performance

Description of customer benefits Advantages and chances of additive manufacturing production	The increased efficiency of handling of fluids contributes to reduction of fuel consumption, and therefore saves the environment. In addition, AM enables the adaption of fluid systems to better fit in the provided space of the car. Depending on the field of application, the form of e.g. the air conditioning system or heat exchanger can be varied to the ordered model. As channels and other geometries can be directly integrated inside the component, AM can significantly reduce waste and the number of needed parts, resulting in higher durability and lower costs. Additively manufactured heat exchangers are functionally superior due to the feasibility of larger surfaces, arbitrary complex geometries, shapes and liquid channels. In contrast, conventional heat exchangers, for example, are often equipped with just a few, geometrically simple liquid channels.
Description of risks along the value chain Disadvantages und risks for the customers and OEMs	New fluid systems have to be designed for AM. Therefore, engineers will have to learn how to combine intelligent structures and functionality using AM-technologies to realize the best performance of the part. However, the integration of new functions raises the complexity of the part, which in turn can increase repair costs for broken parts, as the entire system would have to be replaced. In addition, problems with multi-material design might occur and lead to higher development costs.

Competition

Conventional manufacturing technologies • What manufacturing technologies are used so far? • What are the benefits of the conventional technologies?	The spectrum of conventional fluid systems ranges from simple one-part products like intake or return lines to heat exchangers, which consist of a multitude of parts. In general, these parts are produced by ordinary metal-cutting manufacturing technologies or casting processes, and are standardized. These manufacturing processes are optimized for high volume production. Customization, for instance the production of special formed tubes in low volume, is cost-intensive and can only be realized if urgently needed.

Production costs using AM-technologies compared to conventional technologies		lower		comparable		higher
	Production Costs	☐	☐	☒	☐	☐

Added value through using AM-technologies compared to conventional technologies		low		medium		high
	Benefit	☐	☐	☒	☐	☐

Research Approaches

• Which kind of innovations do already exist in this field of innovation? • What are important research steps that have to be taken to realize future production (future requirements)?	In order to simplify the design process, research in software optimization is pushed. With the aim „to make the link between the rigidity of parametric design and artistic flare“, black box systems are being developed which allow non-designers (customers) to modify already existing designs. The black box system can interpret the design intent during the design process and, as parameters for structural requirements, material characteristics and heating, ventilating and air conditioning (HVAC) requirements are implemented in the software, suggests corrections in order to achieve the optimal part design [HHD06, p.258]. This simplification in the design process raises the attractiveness of the technology by far, as the advantages of AM increasingly appear. In cooperation with Stratasys Inc., researchers at the University of Maryland, College Park (UMD) have developed the first, additively manufactured, plastic heat exchanger [Mar12-ol].

Ability of DM-technologies

• Is the necessary know-how for applying AM-technologies available? • Where are the deficits?		available		partly available		not available
	Development	☒	☐	☐	☐	☐
	Production	☐	☐	☒	☐	☐
	Quality Assurance	☐	☐	☐	☐	☒

Assessment of the Innovation Field

• How do you assess the innovation field?		very low		medium		very high
	Technology Risk	☐	☐	☒	☐	☐
	Market Potential	☐	☐	☐	☒	☐
	Maturity Level	☐	☒	☐	☐	☐
	Competitive Intensity	☒	☐	☐	☐	☐

Reference to other Innovation Fields

• Are there any references to other innovation fields?	The innovation fields *Optimized Tooling* and *Handling of Fluids* are strongly connected to each other, as the realization of optimized cooling structures inside of tools also depends on the knowledge about the optimal design for fluid systems.

Conclusion	give up	put back	pursue	realize
	☐	☐	☒	☐

Figure 2-22: Detailed characteristics for the innovation field Handling of Fluids

Due to the technological complexity of automotive commodities, AM offers a wide range of applications in this field. Besides functional innovations, the need for new alternative power train technologies opens up innovation fields such as Electric Drive. Furthermore, designing and manufacturing of tools can significantly be enhanced by AM.

2.3 Future Applications in the Electronics Industry

In this chapter, the innovation fields for the electronics industry are presented. From these innovation fields, the most promising are selected for concretization.

2.3.1 Idea Creation and Documentation

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

AM provides great potential for innovations in the electronics industry. Against the background of the reference future scenario, 28 product ideas have been developed for the electronics industry manufacturing equipment. These ideas were clustered to 8 innovation fields:

- E1 – Additive Factory;
- E2 – Adaptive Components;
- E3 – Testing Systems;
- E4 – Fuel Cell;
- E5 – Material Combinatorics;
- E6 – Functionally Integrated Parts;
- E7 – Tooling;
- E8 – Handling Systems.

The following section gives short descriptions of all innovation fields, including an exemplary product idea from each innovation field. The characteristics encompass a short description, a draft, the current technical solution, advantages and disadvantages. A more detailed description of all innovation fields and all developed product ideas are part of the confidential study.

Innovation Field E1 – Additive Factory

Additive Factory incorporates the “free-space“ layerwise manufacturing.

Present manufacturing techniques for electronics only offer a limited degree of flexibility. The innovation field *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. Using the Multi-Replicator, multiple layers of semi-conducting material can be processed directly to create p-n junctions, conductors etc. “Free-space” manufacturing machines allow overcoming the current limitations on build-space. Thereby, AM excels at the elimination of cost-intensive tooling and reduction of production time [Wor11c]. Figure 2-23 shows an exemplary idea from this innovation field.

Adaption of Product Quality

Description

Product quality and durability are closely interconnected. In order to guarantee a constantly high product quality, monitoring of a part during the production process is indispensable. A possible solution, e.g. for selective laser melting, is the application of a production process which consists of two complementary control or monitoring systems. The one system is applied for real-time monitoring of the melt pool; the other system is used for the visual inspection of the powder deposition process [CCY+11]. The optical sensor checks the distribution of the powder particles in each layer. The smoother the powder bed, the better is the resulting surface roughness. In case that the measured values are out of calculated tolerances, the machine automatically adjusts parameters for the next layer to realize optimal product quality. This kind of quality control will significantly reduce rejects that are due to defects [Wor11c].

Draft

Advantages/Benefits

- Better control during the manufacturing process
- Direct manipulation of material properties
- Higher product quality
- Less rejects due to defects

Disadvantages/Risks

- Longer manufacturing times
- High equipment costs
- Higher complexity of the machine control systems

Current Technical Solution

Today, quality control takes place after the part is completely finished.

Type of Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-23: Exemplary idea from the innovation field Additive Factory: Adaption of Product Quality

Innovation Field E2 – Adaptive Components

Using AM, components can be integrated to be adaptable to the target part.

The product ideas presented in this field especially focus on *Adaptive Components*, and the range of ideas is quite diverse in this field. Firstly, this innovation field covers adaptive electronics with different shapes and different orientation. For instance, using layer-wise manufacturing, circuits could be printed onto curved surfaces in order to be adaptive to the target part shape.

Secondly, the innovation field encompasses ideas for the integration of electronics, such as sensors, into hardly accessible positions, which enables the evaluation of new data in order to increase the systems adaptability to certain conditions. This can also contribute to improve life-time estimations, optimize maintenance intervals and increase part durability.

Using different materials in one step, altering material properties can be realized.

Thirdly, adaptability can be realized by using different materials to produce 3D-structures with locally altering material properties, such as required conductivity, stiffness, strength properties etc. These electronic parts can e.g. contribute to realize precise pre-stressing of car bodies by exposing the respective areas to an electric current. The implementation of strain gauges in aircraft wings can enable quick changes and adaption of the wing's geometry to different environmental conditions [Wor11c]. An exemplary idea for *Adaptive Components* is shown in figure 2-24.

Changeable Part Properties

Description

The idea behind creating changeable part properties is to use the principle of freedom of design to raise the usability of additively manufactured parts. AM provides the possibility to process materials point to point. Thereby, it is possible to create structures/materials that have different areas of different properties and functions - the so called functionally graded materials [GRS10]. The main purpose therefore is to improve the part properties and/or to increase part functionality. For instance, the usage of materials that differ in conductivity, stiffness and stability, combined with actors to counter steer or indicate local pre-stressing allows changing the way systems react when being stressed. Combined with an electronic control system, a stiffening of targeted system areas is possible [Wor11c].

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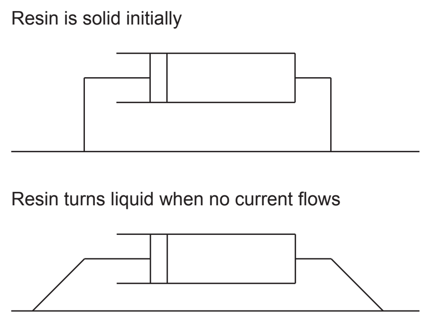

Advantages/Benefits

- Flexible stiffening
- Changeable system behavior, e.g. in case stresses

Disadvantages/Risks

- High system complexity
- Reliability
- Almost no experience in building changeable part properties

Current Technical Solution

Currently, no local adaption of material properties is realized by AM-technologies. Instead, parts are rather stiff.

Type of Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-24: Exemplary idea from the innovation field Adaptive Components: Changeable Part Properties

Innovation Field E3 – Testing Systems

The innovation field *Testing Systems* gives rise to another set of ideas for the application of AM-technologies. Electric switch cabinets or circuit board assemblies and units require highly customized testing systems, which are often produced in small lot sizes. AM excels at high flexibility and a high level of individuality, and can therefore be used to produce testing equipment, including all required attachment points. Thereby, individual testing equipment for every single experiment can be built in a short time [Wor11c].

Using AM, testing systems with individually arranged attachment points can be manufactured.

Furthermore, the test can be carried out in a single step as opposed to the existing solution of sequential testing. Individualizing testing equipment has the further advantage that it is faster to deploy and may even lead to more accurate testing data. Such testing systems can be designed concurrently with the application to be tested [Wor11c]. Figure 2-25 shows an exemplary idea from this innovation field.

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].

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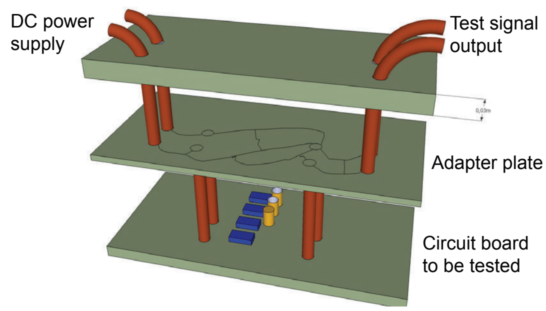

Advantages/Benefits

- 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 Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-25: Exemplary idea from the innovation field Testing Systems: Special Holder for Test Adaptor

Innovation Field E4 – Fuel Cell

Smoother transitions, higher stability etc. due to layer-wise manufacturing

Fuel cells will likely play an important role in transportation in the future. The expected demand justifies the consideration of alternative production techniques in this high-tech realm. As fuel cells are geometrically complex, consisting of a multitude of different materials, AM-technologies are a promising way for its future production and enable economic and functional benefits. As material is deposited layer by layer, multiple materials can be combined on layer level, concurrently enabling smoother transitions, higher mechanical stability, power density and efficiency, and better suited material properties [Wor11c].

Using conventional manufacturing technologies, various masks and tools are required. Compared to AM, the interfaces are more abrupt, which in turn can cause delamination resulting from mismatches in the coefficients of thermal expansion between different materials. AM also improves material utilization rates, which is especially beneficial in case of expensive catalysts and other materials. The usage of AM may also lead to designs being more energy efficient compared to common fuel cells [Wor11c], [Opt10-ol].

This innovation field has many interfaces with other innovation fields. For instance, *Material Combinatorics* and *Functional Integration* are of great importance for the ideas in this innovation field (see innovation field 6 and 7). An exemplary idea for *Fuel Cell* is shown in figure 2-26.

Fuel Cell

Description

A fuel cell usually consists of a variety of complex parts. For instance, parts with different densities like platinum, where dense layers alternate with porous layers. Foamed and spongy components are needed as well. AM-technologies can provide benefit in this instance. Different investigations in this area have already demonstrated that these additively manufactured parts perform equally or better than the components fabricated by conventional manufacturing technologies. E.g. indirect selective laser sintering of graphite composites can be used to produce bipolar plates with superior characteristics [KTL+09]. The production of a one-part fuel cell using AM-technologies might lead to smaller systems, making the technology even more attractive for the automotive industry [Wor11c].

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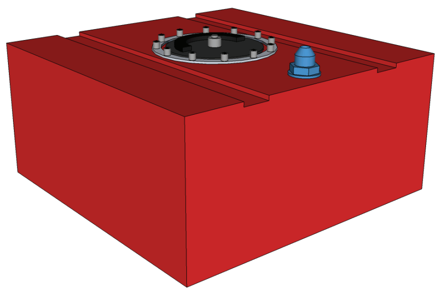

Advantages/Benefits

- One part without any glued surface or welding lines
- Fewer fasteners are needed
- Possible functional integration by e.g. installing sensors etc.

Disadvantages/Risks

- Entire production process is susceptible to errors
- Cost-intense
- Few experience in additive production of high-tech multi-material parts

Current Technical Solution

Many components are assembled to one fuel cell. Miniature fuel cells are produced using Micro-Electro-Mechanical processes (MEMS) and conventional CNC machining processes [KTL+09].

Type of Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-26: Exemplary idea from the innovation field Fuel Cell: Fuel Cell

Innovation Field E5 – Material Combinatorics

The idea of *Material Combinatorics* provides great benefits for the usage of AM, since multi-material design is gaining importance in the construction of electronic parts. The core purpose of applying multiple materials in a part is to provide additional functionality, for instance electrical conductivity, or the required mechanical properties of designed components.

Material combination on layer level is possible.

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. Moreover, components with extraordinary material properties may be realized as well [Wor11c]. Figure 2-27 shows an exemplary idea from this innovation field.

Multi-Material-Combinations

Description

Multi-material design often adds value to a part. A one dimensional multi-material realization where different materials are only placed above each other could be realized by using AM-technologies. Nevertheless, this kind of multi-material part design is rarely needed. As different investigations show, AM-technologies can furthermore be applied for three-dimensional arrangement of different materials in one component [OZ10]. AM could contribute to save time, as for instance the production of a plastic-coated metal requires at least two working steps by using subtractive manufacturing technologies. An AM-machine equipped with a multi-material nozzle would only need one single process step. Furthermore, AM-technologies can be used to fuse e.g. plastic and metal to create multi-material combinations with new material properties. The possible adaption of the material properties in turn increases the range of applications for AM-technologies [Wor11c].

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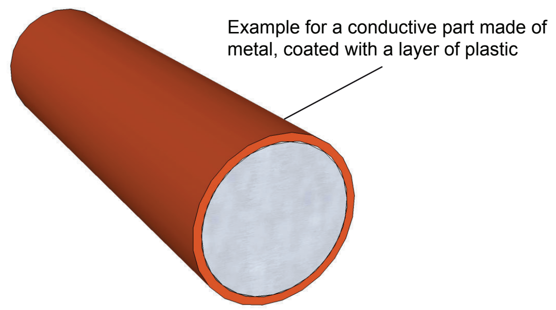

Advantages/Benefits

- Multi-material parts opens up new possibilities for AM-applications
- Only one process step is needed
- New material properties can be generated depending on the used material combinations

Disadvantages/Risks

- Unwanted material degradation
- Higher material costs
- Only little experience so far

Current Technical Solution

Materials are combined using several (expensive) working steps.

Type of Ideas

☐ product update ☐ adaption ☒ innovation

Figure 2-27: Exemplary idea from the innovation field Material Combinatorics: Multi-Material-Combinations

Innovation Field E6 – Functionally Integrated Parts

The idea of functional integration can be applied to electronic devices, especially against the background of increasing miniaturization in the electronics industry. The challenge is the production of devices that exceed today's performance, concurrently enabling smaller package dimensions. Firstly, AM-technologies are suited to meet these requirements through embedding electronics (circuits) into all kind of geometries. Secondly, it is possible to functionally integrate a number of different electronic devices in just one product. Unused space in electronic devices and thereby, the part size can be reduced. This can in turn contribute to more pleasing designs [Wor11c].

Embedded electronics

Increased part performance through functional integration

This innovation field also encompasses ideas, such as the direct integration of functions into the part frame, following the principle of Molded Interconnect Devices (MID)-technology. In addition, product ideas in this innovation field benefit from the flexibility of AM, since existing functions can either be improved or entirely new functions can be implemented [Wor11c], [GRS10]. An exemplary idea for *Functionally Integrated Parts* is shown in figure 2-28.

Individual Boxing

Description

High volume production of electronic devices often uses one and the same box for every variant of the product. This leads to suboptimal conductance or loss of energy (heat conductance). Furthermore, unused space in the boxing is making 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 to 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].

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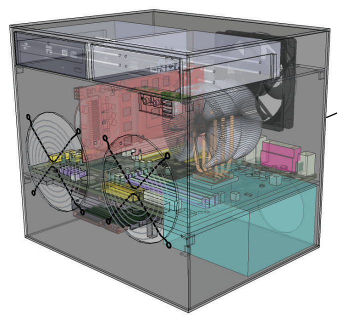

Advantages/Benefits

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

Disadvantages/Risks

- Subsequent changes might be critical
- Boxing has to be optimized for every product variant
- Higher Costs

Current Technical Solution

Standardized boxing.

Type of Ideas

☒ product update ☐ adaption ☐ innovation

Figure 2-28: Exemplary idea from the innovation field Functionally Integrated Parts: Individual Boxing

Innovation Field E7 – Tooling

Due to the rapid technological advance, lifetimes of electronic products are increasingly shortening. Tooling and manufacturing equipment used in the production of electronic parts are required in shorter intervals. In this realm, AM can contribute in various ways. The small lot sizes, in which tools are usually produced, together with meticulous quality standards, generate high expenses.

AM enable indivudual tooling and can function as tooling substitute.

AM-technologies offer the required flexibility and the possibility of multi-material processing, to produce tools in one manufacturing step. Different inserts for tools manufactured in one machine and variably applied in the manufacturing process are some product ideas in this innovation field. Moreover, AM can function as a tooling substitute by manufacturing electronics parts directly with AM-machines [Wor11c]. This idea however is part of the innovation field *Additive Factory*. Figure 2-29 shows an exemplary idea from this innovation field.

Individual Tooling Insert

Description

The production of electronic parts often requires the adaption of machine tools. The production of tools with subtractive manufacturing technologies is rather inflexible and expensive. By applying AM-technologies, individual tooling inserts can be designed for one tool. The modular conception enables flexibly changing individual tooling inserts in just a few hours and less expensive. Furthermore, using AM-technologies, tools consisting of a material mixture of e.g. a combination of different metals might be usable in the future [Wor11c].

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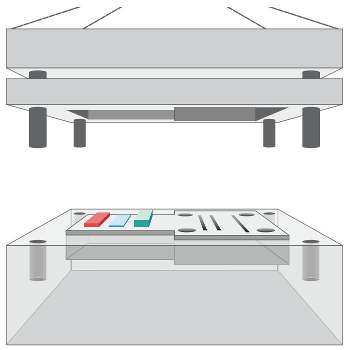

Advantages/Benefits

- Individual components due to high flexibility
- Low manufacturing costs due to modular conception
- Easy to replace in case of damage
- Reduction of machining or tooling costs
- Higher level of standardization for tooling (frames for inserts)
- Reduction of time from idea to production (time-to-market)

Disadvantages/Risks

- Durability
- Availability of materials

Current Technical Solution

Even though rapid tooling is already known and used in different industries, most toolings are still produced with conventional subtractive manufacturing technologies today.

Type of Ideas

☒ product update ☐ adaption ☐ innovation

Figure 2-29: Exemplary idea from the innovation field Tooling: Individual Tooling Insert

Innovation Field E8 – Handling Systems

Light-weight Handling Systems contribute to accelerate processes and increase efficiency.

Handling systems in the electronics industry can potentially benefit from the application of AM-technologies. Due to the flexible use of different materials or the principle of lattice structures, grippers and other manufacturing devices can be produced with a light-weight interior and a hardened frame. Thereby, speed and efficiency of such pick and place systems can be increased and manufacturing processes can be accelerated. In addition, grippers and manufacturing devices can be manufactured with integrated testing functions and adaptive construction mechanisms which enable grasping of different components (size etc.) [Wor11c]. An exemplary idea from the innovation field *Electric Drive* is shown in figure 2-30.

Pick and Place Systems

Description

Pick and place systems for machines shorten the production time, as the unloading process can be accelerated. Such systems require high assembly effort, as they consist of many parts for realizing the kinematics. In addition, these are often very heavy. Using AM-technologies, the frame of the pick and place systems can be designed in lattice structures or using undercuts, combining high stiffness with low weight. The systems can be manufactured in one step, hinges and flexible areas included [Eos06-1-ol]. This guarantees high precision and high accuracy, even if heavy parts or parts of any geometry need to be lifted. A well-engineered pick and place system can contribute to reduce the requirements on personnel concurrently increasing productivity. Further features referring to functional integration, like a quality control can be realized by integrating sensors in the picker arm during the unloading process [Wor11c].

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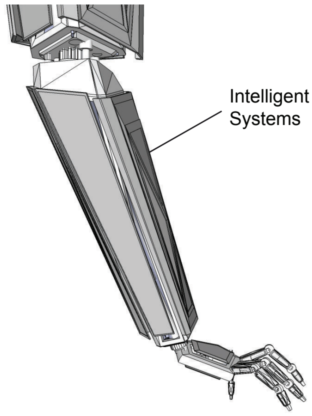

Advantages/Benefits

- Number of parts is reduced
- Faster machine loading due to optimized weight
- Shorter production times
- Less manpower required
- Monitoring of part quality
- Assembly is minimized

Disadvantages/Risks

- Acquisition costs
- Prone to errors

Current Technical Solution

Unloading is usually conducted manually.

Type of Ideas

☐ product update ☒ adaption ☐ innovation

Figure 2-30: Exemplary idea from the innovation field Handling Systems: Pick and Place Systems

2.3.2 Idea Selection

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 their 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 2-32. For the innovation fields, the ordinate intercept shows the chances; the abscissa intercept indicates the risks.

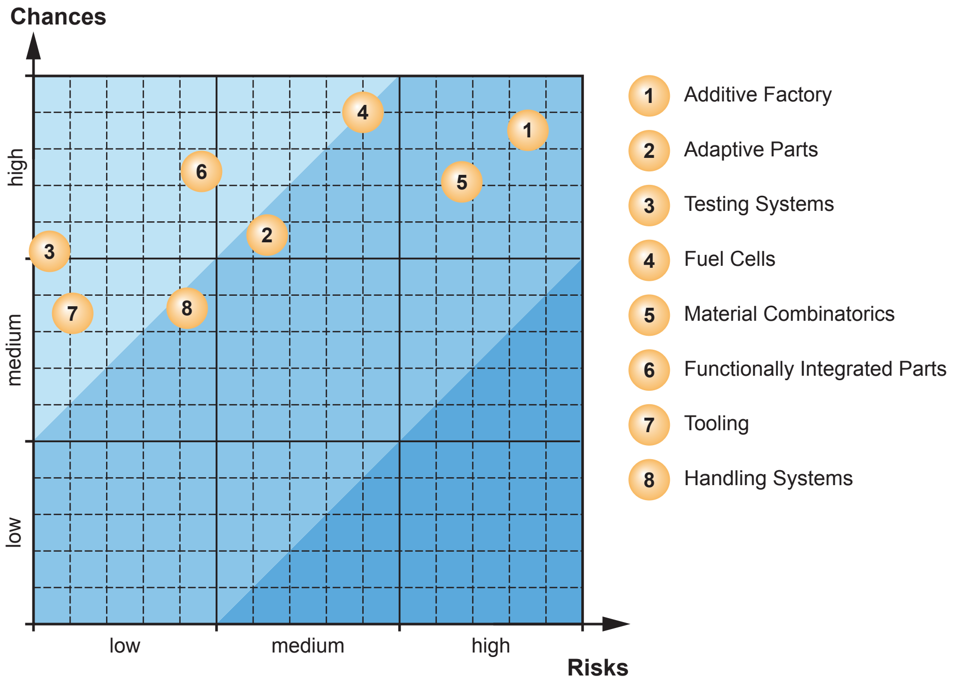

Figure 2-31: Prioritizing innovation fields of the electronics industry using a chances-risks-portfolio

Functionally Integrated Parts and Testing Systems were selected as the most promising innovation fields for the electronics industry.

The closer an innovation field is to the top left corner, the higher the attractiveness of the innovation field for the application of DM. According to the experts' assessment, *Additive Factory* offers the highest potential for the application of DM; concurrently, this innovation field entails the greatest risks. The innovation fields *Functionally Integrated Parts* and *Testing Systems* were assessed as the most promising with regard to DM, due to relatively high chances and low risks.

2.3.3 Idea Concretization

The highly prioritized innovation fields – *Functionally Integrated Parts* and *Testing Systems* – were concretized in more detailed characteristics. The concretization includes aspects, such as a detailed description of the innovation field, and specifies the opportunities and barriers for the application of AM. It also outlines the technical feasibility and the advantages in comparison to the application of conventional technologies. Figure 2-33 visualizes the concretized innovation field *Functionally Integrated Parts*. All concretized innovation fields are part of the confidential study.

Functionally Integrated Parts

Market Performance

Description of the market service

- Product business
- Position in the value chain
- Unique selling points

Using AM-technologies, parts are built layer by layer. Thus, AM enables parts of high complexity, with undercuts, directly embedded components and integrated functions, without applying any intrinsic tools. Especially in the electronics industry, functional integration plays an important role due to progressive miniaturization. With AM-technologies, highly integrated parts can be constructed using a monolithic design and designed individually to better fit the purpose they are needed for. For instance, these components can be optimized for individual applications with regard to size, weight, strength etc. by applying suitable materials and structures. As parts can take any arbitrary geometry and shape and embed any function by using AM-technologies, the range for their application is wide [Wor11c].

Technological product concept

- Product structure
- Key design features
- Hint of possible variants
- Substantial performance data (specification)

The main challenge is the production of devices that exceed today's performance, concurrently enabling smaller package dimensions. The spectrum for functionally integrated parts ranges from adapted housing designs for different variants of one part to specially designed parts for electric engines with e.g. integrated cooling/warming channels in the winding support. Depending on the application of these parts, e.g. a suboptimal conductance or loss of energy due to heat conductance can be countered. Furthermore, AM-technologies are suited for embedding electronics (circuits) into all kind of geometries, and it is possible to functionally integrate a number of different electronic devices in just one monolithic product. Functions can also be integrated into the part frame, following the principle of MID-technology (Molded Interconnect Devices). The technological product concept, including the required materials, strongly depends on the individual application. It is likely that the processability of multi-material-combinations in one single job is an essential prerequisite for exploiting the full potential of AM for manufacturing functionally integrated parts [Wor11c].

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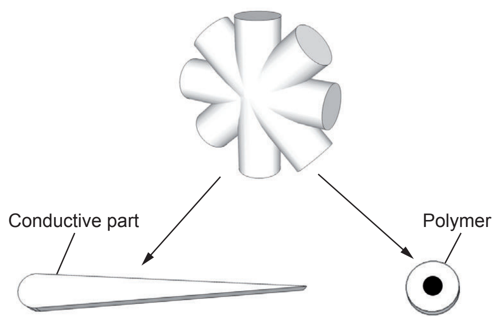


Description of goods and services

How will the product be manufactured?

Functional integration often goes beyond the boundaries of conventional, subtractive manufacturing technologies, as functionally integrated parts often have very complex structures. In general, functionally integrated parts are broken down into subcomponents which are assembled to one piece. AM-technologies excels at high flexibility in design, geometry etc. The AM-technology to be used strongly depends on the required part and material properties [Wor11c].

Technology Performance

Description of customer benefits

Advantages and chances of additive manufacturing production

Additively manufactured, functionally integrated parts can perfectly be adapted to individual purposes/applications whereby part design can drastically be improved and customization of parts in small lot sized becomes possible. In addition, by using individual part structures, the parts are more resistant against working load and therefore, they are more durable. Due to the monolithic design and fabrication, assembly operations can be reduced to a minimum which implies lower production costs [Wor11c].

Description of risks along the value chain

Disadvantages und risks for the customers and OEMs

The adaption and functional integration of parts for a special purpose is often challenging for engineers, especially in terms of design rules and design tools. AM represents a technology which is only advantageous if known how to handle it. Furthermore, an adaption of every single production variant will raise the production costs. Depending on the application, different materials might be needed. Even though a broad range of materials is already available, there might be special materials which are not additively processable [Wor11c].

Competition

Conventional manufacturing technologies

- What manufacturing technologies are used so far?
- What are the benefits of the conventional technologies?

Current technical solutions for manufacturing of multifunctional structures are ordinary metal-cutting manufacturing technologies or casting processes. The needed electronic parts are integrated into the intended building spaces during assembly. As the component is built from several geometrically non-complex parts, the manufacturing process is faster than AM-processes. Moreover, in case of high volume production, manufacturing costs of conventional technologies are lower. In contrast, the higher the number of parts which have to be functionally integrated, the higher the complexity of the assembly process. Ordinary build components can often be disassembled without being destroyed and thus, are easier to repair [Wor11c].

Production costs using AM-technologies compared to conventional technologies		lower		comparable		higher
	Production Costs	☐	☐	☒	☐	☐

Added value through using AM-technologies compared to conventional technologies		low		medium		high
	Benefit	☐	☐	☒	☐	☐

Research Approaches

• Which kind of innovations do already exist in this field of innovation? • What are important research steps that have to be taken to realize future production (future requirements)?	Even though AM-technologies are on the rise, direct manufacturing is still limited to a few application fields, such as the manufacturing of hearing devices [Geb08]. However, AM has already been used for the production of functionally integrated parts, e.g. parts with directly integrated springs or special checking and measurement fixtures for quality control but the availability of general accepted design rules for dimensioning and the design of parts is needed to further push functional integration [Rij11], [WW10-ol]. Functional integration is also an issue for structural health monitoring, printed temperature sensors, functional gradient materials etc. [Opt10-ol].

Ability of DM-technologies

• Is the necessary know-how for applying AM-technologies available? • Where are the deficits?		available		partly available		not available
	Development	☒	☐	☐	☐	☐
	Production	☐	☐	☒	☐	☐
	Quality Assurance	☐	☐	☐	☐	☒

Assessment of the Innovation Field

• How do you assess the innovation field?		very low		medium		very high
	Technology Risk	☐	☐	☒	☐	☐
	Market Potential	☐	☐	☐	☒	☐
	Maturity Level	☐	☒	☐	☐	☐
	Competitive Intensity	☒	☐	☐	☐	☐

Reference to other Innovation Fields

• Are there any references to other innovation fields?	Functionally Integrated Parts can significantly contribute in diverse innovation fields, for instance, *Adaptive Components* and *Testing Systems*, as functional integration into all kind of parts is one of the major advantages AM excels at [Wor11c].

Conclusion	give up	put back	pursue	realize
	☐	☐	☒	☐

Figure 2-32: Detailed characteristic for the innovation field Functionally Integrated Parts

The application of AM provides great potentials for innovations in the electronics industry. Given the close interlacement with other industries, for instance, ideas such as the additive production of fuel cells emerge. Besides, Testing Equipment or Handling Systems for the production of electronics can give rise to promising ideas.

2.4 Deduction of Future Requirements

In this chapter, future requirements on DM-technologies are deduced. First, general requirements that do not relate to technology were identified. In addition to the general requirements, technology-specific requirements are derived by a detailed analysis of the identified innovation fields for the aerospace, automotive and electronics industry. The requirements constitute a profound basis for the deduction of required technological advancements of AM-technologies. The following section describes the deduction of requirements in extracts. A comprehensive assignment of requirements to innovation fields is part of the confidential study.

General Requirements

General requirements influence the performance of a company.

General requirements are decisive for the success of a company, as these influence a company's business performance. Therefore, it is necessary to identify those requirements that are the most significant from the market perspective. The following list provides the identified general requirements:

- High innovation ability;
- Strong competences to provide solutions;
- Strong consulting competences (Pre-Sales-Support);
- Strong competences for maintenance and support (Post-Sales-Support);
- Distinct customer orientation;
- Provision of qualification courses;
- Continuous IT-support from CAD-file creation to part measurement.

Technology-Specific Requirements for the Aerospace Industry

The analzyed innovation fields have many requirements in common.

Technology-specific requirements are directly technology-related, and have been derived from the innovation fields developed for the three industries. As many of the identified requirements are decisive for more than one innovation field, the following figure 2-33 shows an extract of the assignment indicating which requirements (row) the innovation field (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.

Requirements Matrix **Question: "Which requirement (column) does the innovation field (row) impose on DM-technologies?"**	**Requirements**	High process stability	Certification	Provision of design rules	On-line quality control	Processability of different materials	Building up on existing 3-D surface structures	Acceleration of AM-processes	Automated integration of AM-processes	Database containing properties of AM-materials	Processability of different materials in one job	High dimensional accuracy	Recyclability	Large build chamber volume	...	Integration of electronic circuits	Availability of self-healing materials properties
Innovation fields																	
Ai1 – Aircraft Interior		X	X	X	X	X	X	X		X		X					
Ai2 – Multifunctional Structures		X	X	X	X	X		X	X	X	X	X	X			X	X
Ai3 – Energy Saving Structures		X	X	X	X		X		X	X	X	X	X			X	
Ai4 – Monolithic Structures		X	X	X	X		X	X	X				X	X			X
Ai5 – Morphing Structures		X	X	X	X	X		X		X	X	X	X	X		X	
Ai6 – Deployable Structures		X	X	X	X	X			X			X	X				X
Ai7 – Smart Joinings		X	X	X	X	X	X		X							X	
Ai8 – Out-of-Chamber Manufacturing		X	X	X			X	X			X						
Ai9 – Manufacturing on Demand		X	X				X	X	X		X			X			
Au1 – Functional Body-in-White		X	X	X	X	X	X	X	X	X	X		X	X		X	
Au2 – Individualized Interior		X	X	X	X	X	X			X		X					
...																	
E7 – Tooling		X	X	X	X	X			X	X	X		X	X			
E8 – Handling Systems		X		X				X				X		X		X	

Figure 2-33: Deduction of requirements from innovation fields

- 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 additively processed materials** (e.g. thermal characteristics, tensile strength etc.) is very important for *Multifunctional Structures* and *Functional Body-in-White* in order to assess functional capability under all circumstances.

The application of AM in the considered innovation fields, gives rise to a broad variety of requirements. Exemplarily, high process stability, certification, design rules and the ability to control the part quality during the production process will play a key role in the future.

2.5 Summary

120 application ideas in 27 innovation fields were developed.

The selected reference scenario combinations for the aerospace, automotive and electronics industry with the greatest impact on the future of DM were used to develop ideas for future applications of AM. The spectrum of the identified DM-applications encompasses 120 ideas. These were clustered to 27 innovation fields according to their similarity, and prioritized based on the assessment of the chances and risks. The innovation fields identified to be the most promising for the application of AM-technologies in future were concretized in specific expert workshops as well as through market research.

For the aerospace industry, the experts identified the following innovation fields to be the most 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 phase or to different high-speed phenomena, respectively. Thereby, the flight performance can significantly be improved and fuel consumption can be reduced.
- **Multifunctional Structures** includes ideas for 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 into a part can even contribute to realize adaptronics or self-optimizing part properties.

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

- **Handling of Fluids** focus 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** encompasses ideas for integrating channels into tooling parts to improve the durability and resistance of tools. Cross-sections of cooling channels can take any shape whereby uniform heat dissipation and quicker cooling processes can be achieved.

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

- **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 a set of ideas around electric switch cabinets or circuit board assemblies. Additively manufactured testing equipment can be produced including all required attachment points whereby tests could be carried out in a single step.

High process stability, certification, design rules and on-line quality control processes are decisive for many innovation fields.

Based on the analysis of the innovation fields, requirements on further 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. High process stability, certification, automated integration AM-processes and the ability to control the part quality during the production process represent basic requirements across the most innovation fields, just to name a few.

High innovation ability is crucial for the success of a company.

Besides the technology-specific requirements, general requirements that relate to the performance of a company were identified. Exemplary requirements on companies are:

- High innovation ability;
- Strong problem solving competences;
- Distinct customer orientation.

3

Future Requirements on Direct Manufacturing

An expert survey was conducted to identify the most important requirements.

To enable AM-technologies for DM of the identified (future) applications, it is necessary to align the technology development with current and future requirements each application imposes on DM-technologies. This enables the AM-industry to develop and pursue consistent technology strategies and to bundle available competences to effectively advance AM-technologies to DM-technologies. To identify the most important requirements, the Heinz Nixdorf Institute and the Direct Manufacturing Research Center conducted an expert survey on current and future requirements on DM-technologies. The expert survey is available in the appendix A1.

Structure and Proceeding in the Expert Survey

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 such as 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 send to **325 contacts** qualified as AM-experts; **56 contacts (17%)** completed the survey successfully.

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 (chapter 3.1). 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 (chapter 3.2). The third part encompasses the assessment of 19 technology-specific requirements regarding their significance and the technologies' performance concerning these requirements (chapter 3.3). The final part comprises final statements of the participants and indicated research fields of interest. This chapter provides an excerpt of these results; detailed results are part of the confidential study.

3.1 General Information

This chapter presents the results of the first part of the survey which 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, the size of the company they are working in (number of employees) and the development of the revenues.

Activity Field of the Participants

The majority of the participants are technology experts.

91% of all participants in the survey indicate to have expertise in the field of technology and 32% in market/competition. 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, such as service providers.

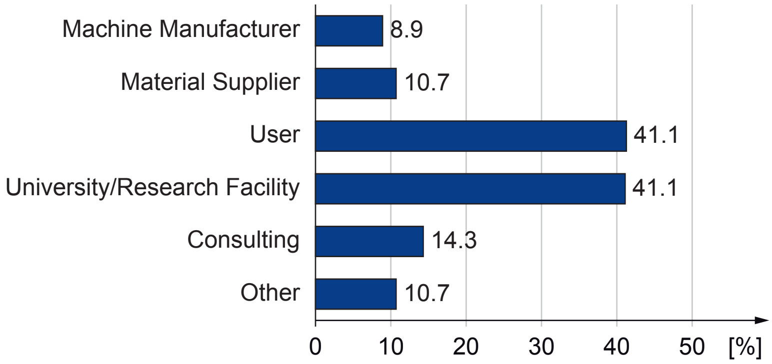


Figure 3-1: Part of the value chain the participants are working in (in percentage terms)

Figure 3-2 illustrates the heterogeneous composition of the participants, as the range covers all company divisions. The vast majority of the participants (77%) specify to work in research and development. With 23%, the management division also comprises a relatively large proportion.

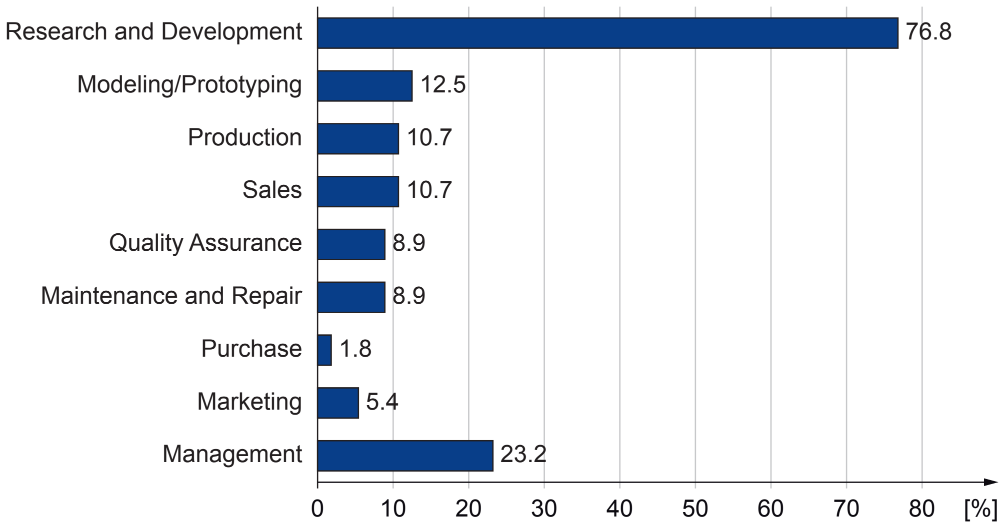


Figure 3-2: Company divisions the participants are working in (in percentage terms)

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 division (see figure 3-2).

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

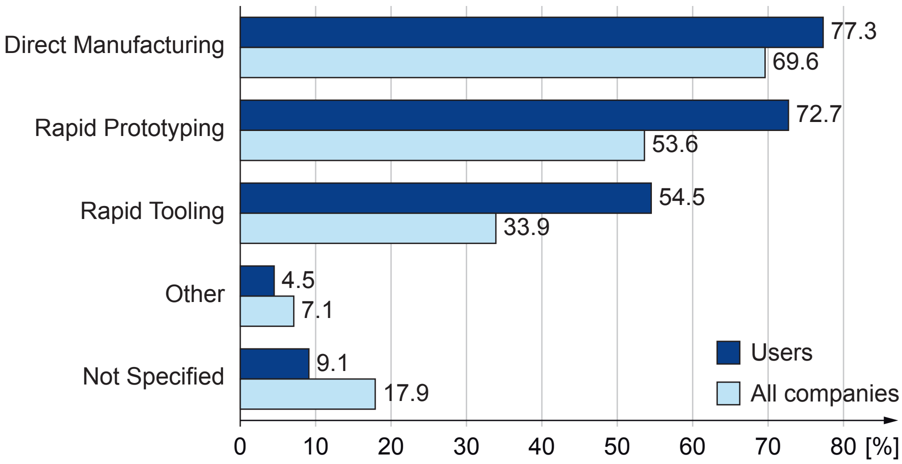


Figure 3-3: *Usage of AM-technologies (in percentage terms), **differentiating the users of AM (dark blue) and all participants (pale blue)***

Number of Employees and Development of the Revenues

The survey addressed companies of different sizes. The majority of **all participants** (34%) are working in companies with less than 100 employees. 18% and 23% of the used data set represents participants from companies employing 1,000 to 5,000 workers and more than 20,000 workers, respectively. 23% of **the users of AM-technologies** represent companies with less than 100 employees and another 23% are working for companies employing between 1,000 and 5,000 workers. 32% of the users indicated to work in a company with more than 20,000 employees.

Apart from the overall size of the company, the participants were also asked to make a statement about the **number of employees working in the field of AM**. Companies with less than 1,000 workers employ around 50%-70% of workers in AM. This is due to the fact, that companies which solely work around the field of AM are usually of smaller size. By contrast, companies with more than 1,000 workers employ less than 0.5% of their workforce in the field of AM. In absolute terms however, bigger companies employ a comparatively large number of employees in the field of AM.

Figure 3-4 shows the **revenues the participants indicated for their companies and for the field of AM, especially pointing out the revenues for the users of AM-technologies** (Upper part: all participants; lower part: users of AM). About 36% of all participants specified the company's revenues of more than 100 Mio. EUR in 2010; 25% generated less than 5 Mio. EUR.

Regarding the revenues in the field of AM, 48% of all participants indicated the revenues to be less than 1 Mio. EUR. It is particularly noteworthy that about 16% of the companies generated between 1 and 10 Mio. EUR in 2010. Approximately **14% of all participated companies generated more than 10 Mio. EUR in the field of AM.**

Approximately 55% of the users of AM specified the overall revenues to be more than 100 Mio. EUR. With regard to the revenues attributed to AM, 46% indicated to generate less than 1 Mio. EUR and 23% between 1 and 10 Mio. EUR. **18% of the users of AM specified the revenues attributed to AM to be more than 10 Mio. EUR.**

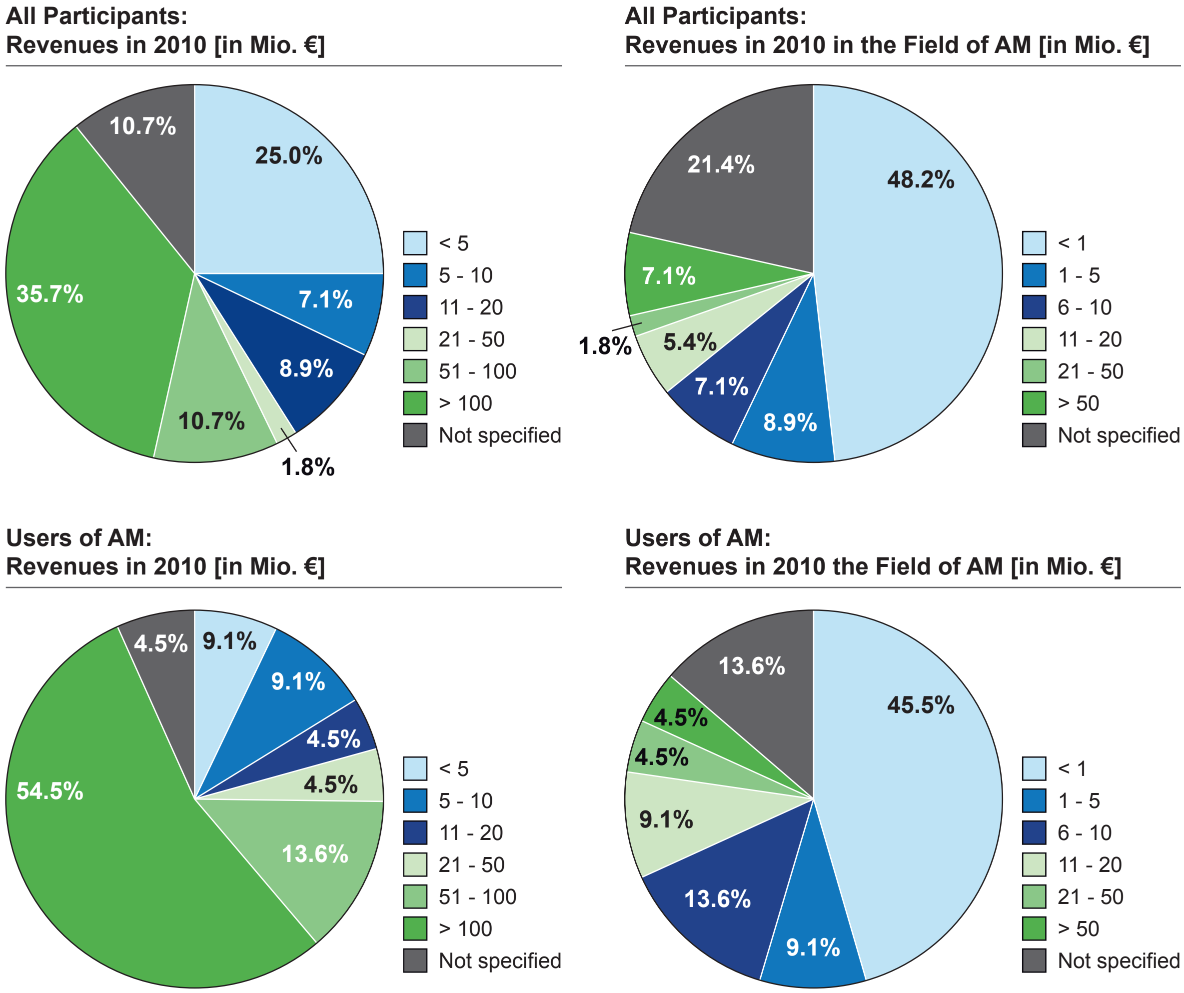


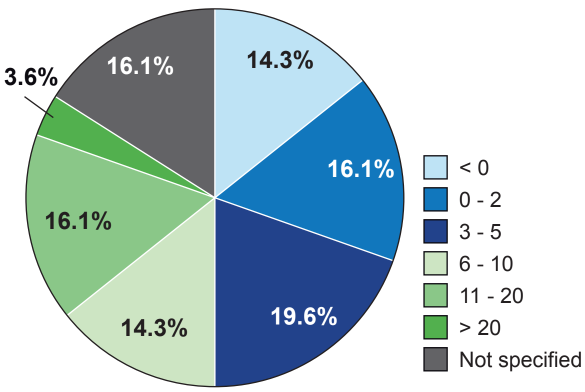
Figure 3-4: Revenues of the company and in the field of AM, ***differentiating data for all participants (upper part) and the users of AM (lower part)*** *(in Mio. EUR)*

Taking a look on the development of the revenues in figure 3-5, it is noticeable that approximately 20% of all participants name growth rates higher than 11%, whereas only 18% of the users name growth rates higher than 11%. This is mainly due to the fact that 60% of the machine manufacturers and more than 80% of the material suppliers indicate growth rates in the range from 11% to 20%. The majority of the users (41%) indicated a growth rate between 6% and 10%.

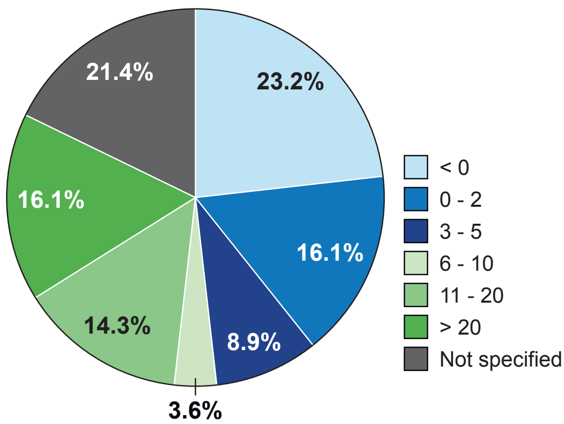
Revenues in the field of AM are progressively growing.

With regard to the development of the revenues in the field of AM, it is particularly noteworthy that **30% of all participants and 52% of the users of AM specify the revenues attributed to AM growing by more than 11%.** These enormous growth rates show the increasing penetration of AM-technologies.

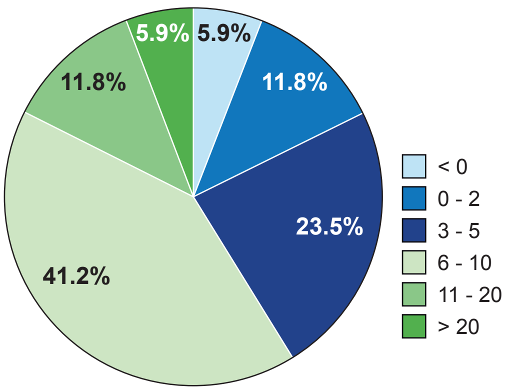
All Participants: Development of Revenues [annual growth rate in %]



All Participants: Development of Revenues in the Field of AM [annual growth rate in %]



Users of AM: Development of Revenues [annual growth rate in %]



Users of AM: Development of Revenues in the Field of AM [annual growth rate in %]

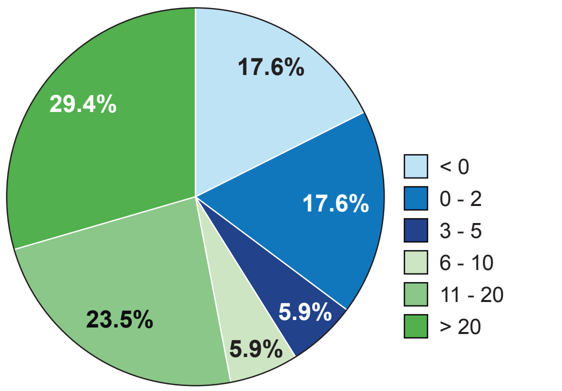


Figure 3-5: Development of revenues of the company and in the field of AM, ***differentiating data for all participants (upper part) and the users of AM (lower part)*** *(in percentage terms)*

The expertise of the survey participants is wide-ranging. A clear majority of experts indicate to already use AM for Direct Manufacturing. 30% of all participants and 54% of the users of AM specify annual growth rates higher than 11% in the field of AM which shows the increasing penetration of AM-technologies.

3.2 General Requirements

General requirements relate to the performance of a company.

In this chapter, the results of the second part of the survey are provided. The goal of the second part is the identification of the most relevant, general requirements today and in the future. General requirements are overall requirements that do not relate to a specific technology; they are rather related to a company's performance and need to be fulfilled for being successful. Therefore, the survey first asked the experts to judge the current and future significance of the requirements for the DM-industry, differentiating the significance for machine manufacturers (MM) and material suppliers (MS) on a scale from "0" to "4" (no significance up to high significance). Secondly, the experts were asked to assess how well the listed companies perform regarding these requirements (degree of performance) using a scale from "0" (i.e. there is a call for action for the company) to "4" (i.e. the company has got a distinctive strength concerning this requirement). This chapter encompasses the results for the current and future significance of the requirements. The results of the company's performance are provided in the confidential study.

In figure 3-6 for each general requirement, the average current (blue color) and the future significance (green color) are visualized, differentiating the significance for machine manufacturers (bullets) and material suppliers (triangles).

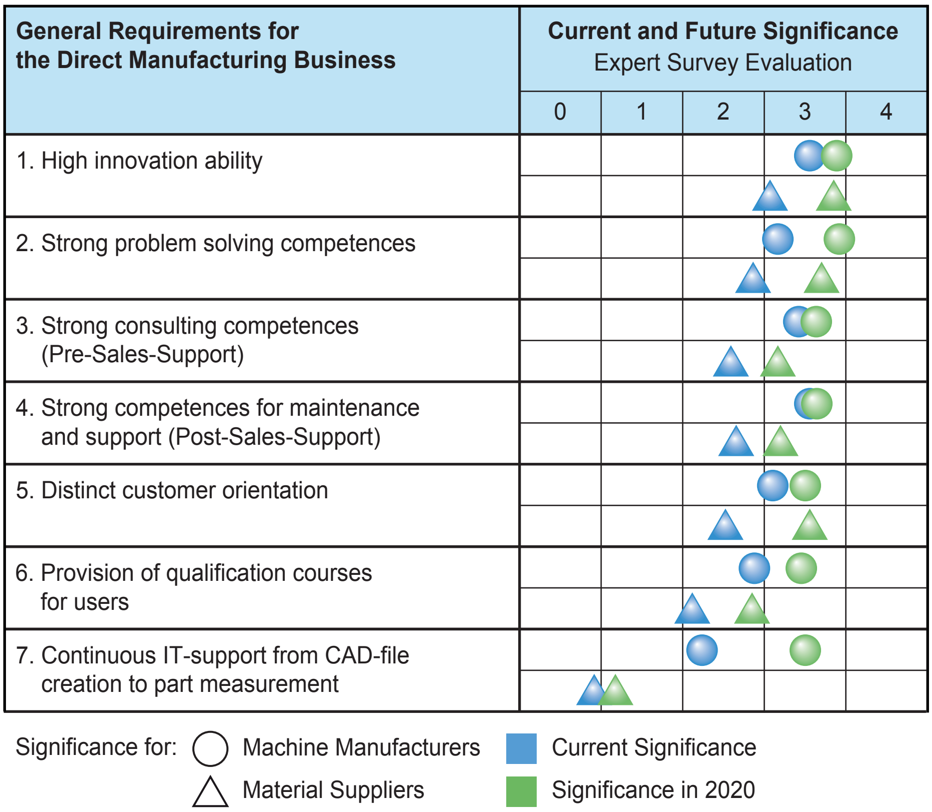


*Figure 3-6: Current and future significance of general requirements for machine manufacturers and material suppliers – Overall evaluation **(all participants)***

At first glance, the **overall evaluation (all participants)** shows that the significance of all listed requirements will increase in future. In addition, all requirements are assessed to be more significant for machine manufacturers than for material suppliers today and in the future. For material suppliers, the current significance of all the listed requirements is indicated as low to medium, but it will considerably increase in future.

In the future, the requirements will gain in significance.

- **High innovation ability** has the highest significance today, for both, machine manufacturers and material suppliers, and will continue to be so in future.

High innovation ability is crucial for material suppliers and machine manufacturers.

- The requirement **strong problem solving competences** currently has a relatively minor significance, but its significance will increase in the future for both groups.
- For machine manufacturers, especially a **continuous IT-support from CAD-file creation to part measurement** will considerably gain in significance, while – compared to other requirements – it has the lowest significance for their business of today. For material suppliers, this requirement is not relevant.
- **Pre-Sales and Post-Sales-Support** as well as a **distinct customer orientation** are and will continue to be of high importance for machine manufacturers. For material suppliers, especially, *a* distinct customer orientation will be crucial for the business of tomorrow.

For material suppliers, a distinct customer orientation is decisive.

Given the fact, that the set of experts consisted of people from various positions in the value chain, a separate evaluation of general requirements that solely accounts for answers of users of AM-technologies is conducted. Their assessment is of pivotal importance for all actors on the market. **Figure 3-7 illustrates the significance for the general requirements from the perspective of the users of AM.** For each requirement, the average current (blue color) and the future significance (green color) are visualized, differentiating the significance for machine manufacturers (bullets) and material suppliers (triangles).

Differentiating the significance profiles in Figure 3-6 and Figure 3-7, **users generally concur with the residual experts**, concerning their weighting of the requirements' significance in 2020. Only their judgement of the future significance of *Continuous IT-support from CAD-file creation to part measurement* is lower than average. Hence, this requirement appears to be of minor importance for the users of AM.

However, **the users' assessment of the current significance crucially stands out**. Across all requirements they unanimously judge the importance today as way higher than the remaining experts. For instance, they rated the current significance of *distinct customer orientation* for material suppliers "2.5", while on average the assessment was "1.9". Consequently, participants from research & development, machine manufacturers etc. must have rated this requirement significantly lower.

Users of AM judge the current significance of many requirements higher than other participants.

Furthermore, differentiating the significance for machine manufacturers and material suppliers it is evident that the evaluation from users' perspective considerably deviates from the overall evaluation, as both significance values are more closely aligned.

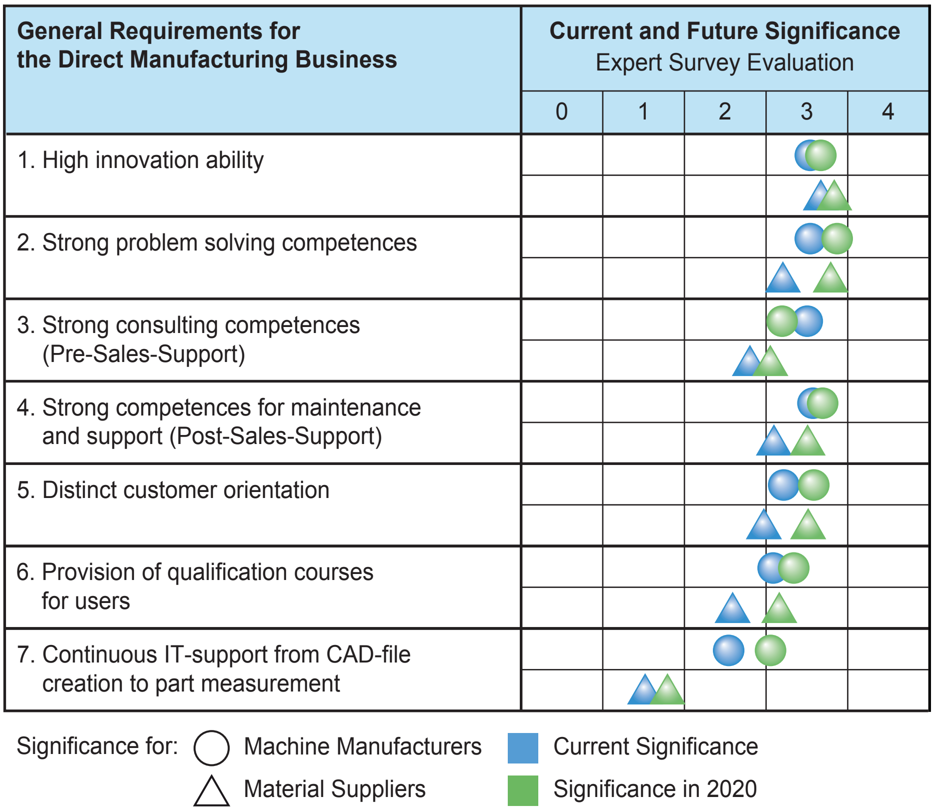


*Figure 3-7: Current and future significance of general requirements for machine manufacturers and material suppliers – **Evaluation from the perspective of the users of AM***

Generally, the results indicate a distinct tendency to an increased future significance of the given general requirements. Users of AM lean towards assessing the increase as substantially lower than other partifipants, as they rank the current significance higher. High innovation abililty and strong problem solving competences have the highest significance today and in the future. All requirements are and will be more significant for machine manufacturers than for material suppliers.

3.3 Technology-Specific Requirements

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

In this chapter, the results of the third part of the survey are provided. The goal of this part of the survey is the identification of the most relevant, technology-specific requirements today and in the future. These requirements are directly technology-related, and have been derived from the innovation fields developed within the project (see chapter 2). The experts were first 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). Secondly, the experts estimated each technology's performance 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).

The goal of this assessment is the identification of those requirements which will be crucial for the business of tomorrow. Based on the comparison of the future relevant requirements and the technologies' performance regarding these requirements, the need for action for further development and optimization of the technology in accordance to (possible) future applications can be deduced.

3.3.1 Evaluation of Current and Future Significance of Technology-Specific Requirements

This chapter encompasses the results for the significance of technology-specific requirements. In figure 3-8, the current (blue color) and the future significance (green color) for all technology-specific requirements is visualized.

Technology-Specific Requirements for the Direct Manufacturing Business	**Current and Future Significance** Expert Survey Evaluation				
	0	1	2	3	4
1. Build chamber volume (V in m³)					
a) V < 1 m³					
b) 1 m³ ≤ V ≤ 8 m³					
c) V > 8 m³					
2. Build-up rates (production speed at highest quality in cm³/h)					
a) 1 - 10 cm³/h					
b) 11 - 40 cm³/h					
c) 41 - 100 cm³/h					
d) > 100 cm³/h					
3. Minimal surface quality of parts with highest quality (average surface finish R_a)					
a) R_a > 10 µm					
b) 5 µm ≤ R_a ≤ 10 µm					
c) 1 µm ≤ 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					
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 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)					

Current Significance — Significance in 2020

Figure 3-8: Current and future significance of technology-specific requirements

Outstanding requirements: High process stability, a database for AM-materials, on-line quality control processes, certification and design rules

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

- **High process stability** (No. 15) is assessed to be an outstanding requirement for the penetration of AM in future.
- A **database containing properties of AM-materials** (No. 18) 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. 12a) play a larger role than on-line control processes (No. 12b). 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 industry manufacturing equipment.
- **Design rules** (No. 17) and **recyclability of materials** (No. 19) 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. 8b) and **fire resistance of AM-materials** (No. 9a) are judged to become important in future, respectively.
- With regard to the quantifiable requirements, it is noticeable that the requirements on larger **build-chamber volume** of AM-machines (No. 8b, 8c) 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. 4).
- Furthermore, **lower maintenance costs** (No. 7) are judged as more important than **lower machine incidental acquisition costs** (No. 6).

Processing of different types of material within one job and building up on 3-D surfaces are the requirements with the largest deviation between the current and future significance.

According to the experts' assessment, a large number of requirements will have a medium significance in future. As their current significance is ranked as rather negligible, these are requirements with the largest deviations between the current and future significance. The *processing of different types of material within one job* (No. 10b), the ability of AM-machines for *building up on 3-D surfaces* (No. 11b) and *processing shape memory alloys* (No. 8d) as well as an *automated integration of AM-machines into existing production lines* (No. 13b) and *highly integrated AM-machines* (No. 13c) are some exemplary requirements with large deviations related to machine ability.

All in all, it is, however, striking that there are considerable discrepancies between the requirements deduced from developed innovation fields and the experts' assessment of the requirement's significance. A large number of the requirements that are crucial for the realization of the application ideas from the innovation fields seem to be of minor importance from the experts' perspective. For instance, larger *build-chamber volume* is required for the realization of a large number of product ideas developed for the aerospace or automotive industry, such as *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 business with AM.

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 provision of design rules are assessed to be outstanding for the penetration of AM in future. Automated integration of AM-machines into existing production lines and highly integrated AM-machines are requirements with the largest deviations between the current and future significance.

3.3.2 Evaluation of the Technologies' Degree of Performance

This chapter presents the technologies' performance with regard to selected technology-specific requirements in order to deduce the need for action for each technology. Based on the assessment in the survey, the arithmetic mean was 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.

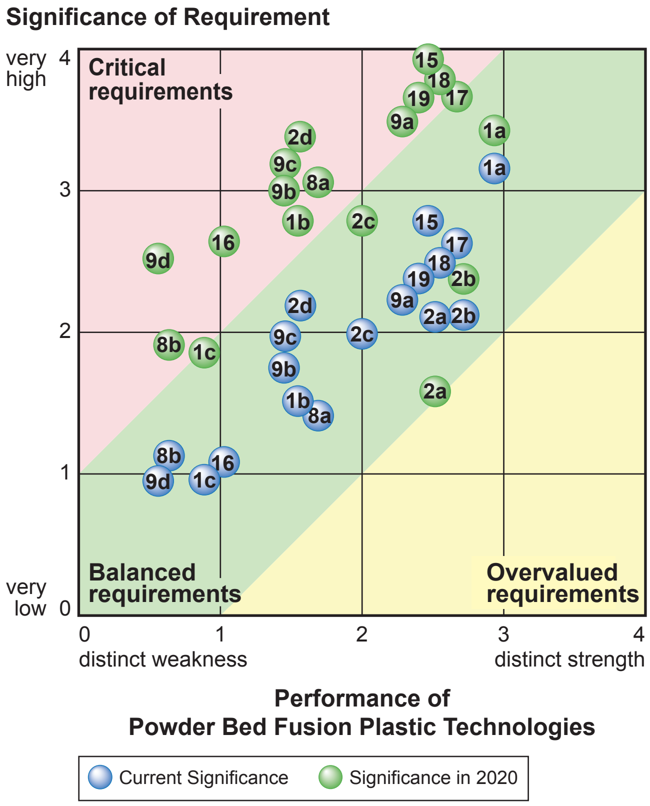
In the significance-performance portfolio, the ordinate intercept shows the significance of the requirements; the abscissa intercept indicates one technology's degree of performance regarding the requirements. In the portfolio, three areas can be distinguished:

- 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 business.

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

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

Figure 3-9 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

8. Processability of materials with AM-machines
8a) Carbon-fiber-reinforced polymer (CFRP)
8b) Liquid crystalline polymers (LCP)

9. Availability of new material properties
9a) Fire resistance
9b) Thermal conductivity
9c) Electrical conductivity
9d) Self-healing properties

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

Figure 3-9: 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.

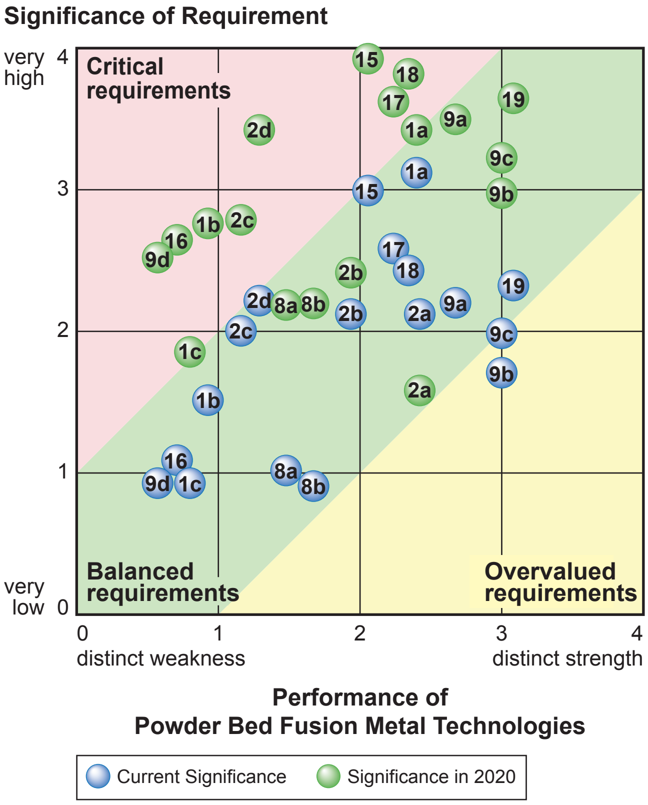
The requirement *build-up rates > 100 cm³/h (No. 2d)* is already considered as almost critical today. Therefore for instance, research that contributes to the production speed could promote Powder Bed Fusion Plastic Technologies in the future. The amount of research that has to be conducted to meet a 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. 9d)* requires much more effort in development than increasing *process stability (No. 15)* 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 little efforts to suit future requirements.

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

Figure 3-10 shows an excerpt of the significance-performance portfolio for Powder Bed Fusion Metal Technologies. The evaluation of the survey results shows that today's requirements are already met sufficiently by the technology. According to the participants of the survey, some future requirements can already be fulfilled by the technology today. This implies that regarding these requirements, e.g. *recyclability of materials (No. 19)* market demand for improvements is low. Even though, with regard to *build-up rates (No. 2d)*, major advancements are required. In contrast to the expert's assessment of Powder Bed Fusion Plastic Technologies, the *process stability (No. 15)* of Powder Bed Fusion Metal Technologies is judged as almost critical today and needs to be improved continuously.

Process stability of Powder Bed Fusion Metal Technologies is assessed as almost critical today.



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

8. Processability of materials with AM-machines
8a) Magnesium
8b) Shape memory alloys (SMA)

9. Availability of new material properties
9a) Fire resistance
9b) Thermal conductivity
9c) Electrical conductivity
9d) Self-healing properties

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

Figure 3-10: Extract from significance-performance portfolio for Powder Bed Fusion Metal Technologies (e.g. Selective Laser Melting)

Furthermore, 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. 9)*, it is striking that the significance of materials with *self-healing properties (No. 9d)* is expected to be very 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. 9b, No. 9c)*, as the future significance correlates with the current technology performance.

Requirements on materials with properties, such as thermal and electrical conductivity are already met.

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

Fused Layer Modeling Technologies partly meet future requirements.

Figure 3-11 shows an excerpt of the significance-performance portfolio for Fused Layer Modeling Technologies. The evaluation of the survey results shows that Fused Layer Modeling 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. 9a)*. 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.

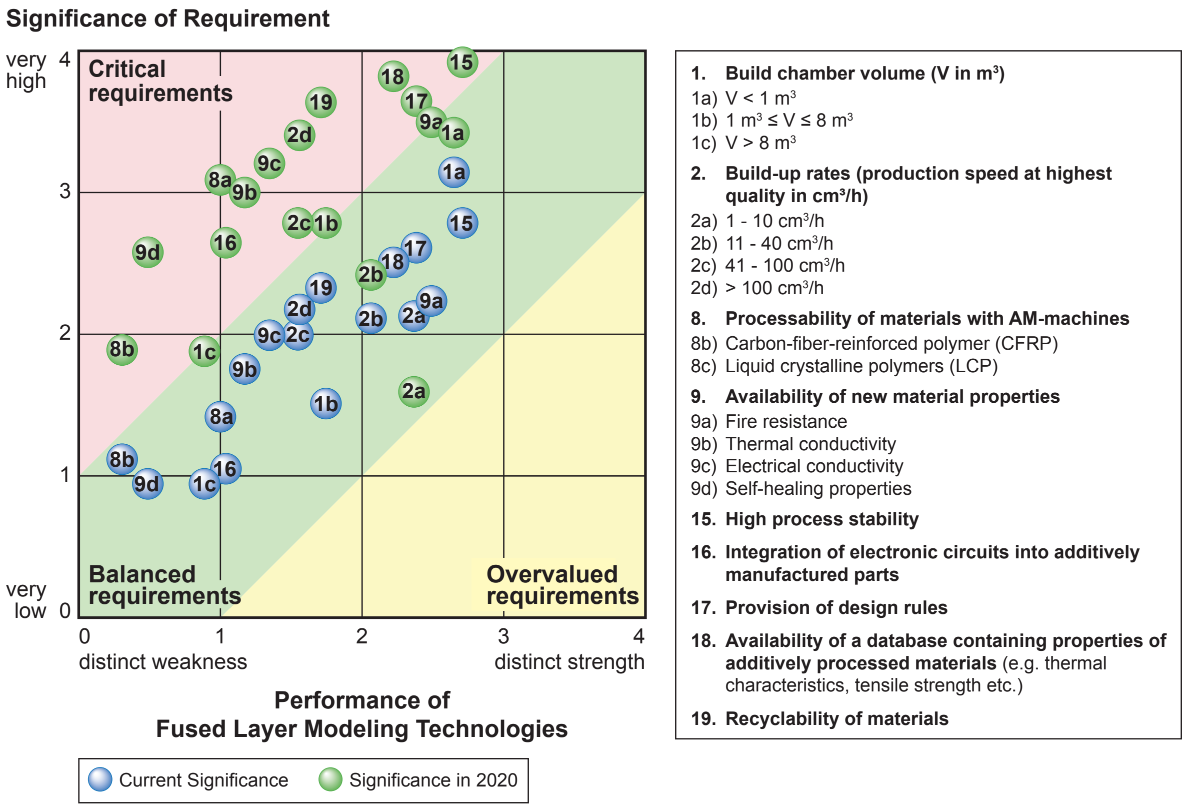


Figure 3-11: Extract from significance-performance portfolio for Fused Layer Modeling Technologies (e.g. Fused Deposition Modeling)

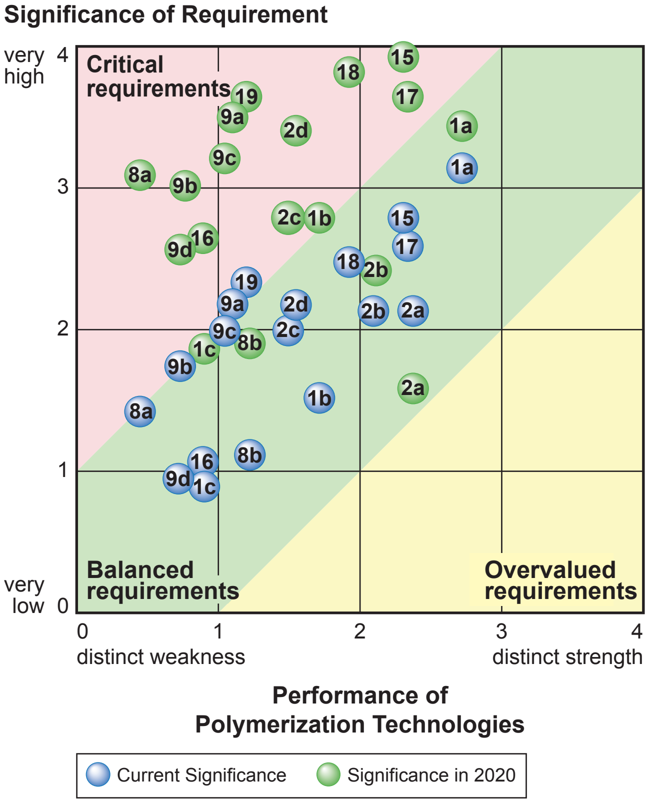
In the future, research is required with regard to recyclability and new properties of AM-materials for Fused Layer Modeling Technologies.

The future competitiveness of Fused Layer Modeling Technologies will furthermore depend on the *recyclability of materials (No. 19)* and the *availability of new material properties (No. 9)*. Especially, *self-healing material properties (No. 9d)* 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. 8b)*, 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)*.

Polymerization Technologies (e.g. Stereolithography)

Some requirements are already critical today for Polymerization Technologies.

Figure 3-12 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
8. **Processability of materials with AM-machines**
   8b) Carbon-fiber-reinforced polymer (CFRP)
   8c) Liquid crystalline polymers (LCP)
9. **Availability of new material properties**
   9a) Fire resistance
   9b) Thermal conductivity
   9c) Electrical conductivity
   9d) Self-healing properties
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**

Figure 3-12: 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 (8b)* or the availability *of new material properties (9)*. Furthermore, the *recyclability of materials (19)* 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, as the significance of almost all requirements is indicated to increase in the future. 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 additively processed materials (18).*The requirements *build chamber volume (1)* and *build-up rates (2)* are uncritical today as well as in the future, due to the fact that the technology performance largely correlates with the requirements' significance. Here, just slight technology advancements are needed.

The different 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.

3.4 Final Statements and Research Fields of Interest

In addition to the general information specifying the profile of the participants and the assessment of the general and technology-specific requirements, the survey asked the experts to name fields of research and action that are of great importance for them within the context of AM. The most frequently mentioned fields are summarized to categories, which are shortly described in the following.

- **Material research** is regarded as an action field of great importance by a large majority of the respondents. This encompasses the development of new materials that improve or expand the capability of the technology for a broader industrial application as well as the qualification of existing materials for AM. Another aspect mentioned relates to accurate and reliable properties of usable materials, for instance such as material aging properties. Moreover especially for the users, technical requirements on material such as thermal and electrical resistance and isolation play an important role. Improved interaction between process and material as well as so-called hybrids – bonds between metal and plastic components with electromechanical functions for electronic components – are other fields of interest.
- The **development of new machines** is indicated to be highly important. One challenge AM especially faces is multi-material processing e.g. the usage of several materials on the same machine. Another aspect frequently mentioned is attributed to the *build size of parts* that is limited to the build chamber volume. This relates to *batch processes*, i.e. the production of one part takes the same time as manufacturing a whole batch of parts.
- A clear majority of the participants indicated **process optimization** regarding aspects such as robustness, reproducibility, machine reliability etc. as an important field of action. This also comprises the enhancement of the productivity/throughput of all systems while maintaining consistent 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. Pre and post processing cannot be optimally performed; set-up times significantly reduce the performance of AM-machines. Other aspects named with regard to process optimization are process automation, real-time process

monitoring and alarms as well as real-time process control. In this context, some experts indicate the so-called **Continuous Additive Manufacturing** as the next obligatory required evolution step to push AM towards DM.

- Another field of research mentioned to be highly important is **process integration**, focusing the integration of AM-processes into conventional manufacturing processes.
- Many of the respondents address the **economic efficiency of AM-technologies**. Firstly, low-budget AM-machines, and secondly, process efficiency are mentioned as important fields of action. Within the context of process efficiency, the reduction of additional costs, such as costs for removal of restraints, finishing of parts etc. is of great importance.
- **Quality assurance** also represents an important field of action for the surveyed experts. 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 are just 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 monitoring and quality control procedures as well as Non-Destructive Inspection (NDI) are mentioned.
- **Part properties** also constitute a major field of action. The points of interest are: homogeneous temperature distribution, integrative functional lightweight structures in multi-material design, lattice structures, prediction and reduction of distortion, just to name a few.
- 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”. For example, automated finishing techniques are named as fields of research.
- **AM-compatible design** is quoted as another major field of action. Particularly noteworthy is that a large number of the participants regard design rules as an important step from AM towards 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 the freedom of design have an almost limitless potential to impact every product’s design. For instance, the usage of AM for bionic product designs highly ranks on the participants agenda.
- To increase the acceptance of AM, **common standards** have to be elaborated. 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.

- **Education** is especially frequently mentioned as an important aspect. To make AM-technologies more accessible to educational institutions, it is necessary to transfer knowledge in teaching and training qualification. In turn, knowledge from research institutions has to be transferred into practice. Moreover, it is required to make both new and existing AM-users across all of the applicable sectors aware of AM's potential. Therefore, education of the industry on the capabilities for the use of tooling, fixtures, assembly and end use parts is also mentioned by the participants of the survey.
- **Future research** is necessary to increase the penetration of AM. Therefore, developments of existing and untapped business areas have to be anticipated in order to early identify the success potentials of tomorrow and to develop ways to exploit these potentials on time. Quoted fields of interest are: concept model realization for macro testing of micro-electromechanical systems (MEMS) devices concepts, functional realization of MEMS (micro and mesoscale), applications for aircraft interior, design parts, air ducts, medical sector as well as specific tools with a relatively low number of actuation mechanisms that are generally produced in small-volumes and that have to be rapidly available.
- **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.
- **Supply Base** seems to be highly ranked on the participants' agenda. One central challenge is attributed to the quantity of existing service bureaus as well as to the quantity of raw material suppliers.
- The **link between CAD-model and analysis tools** for taking full advantage of AM's possibilities is regarded as an action field of great importance, as 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.

3.5 Summary

The Heinz Nixdorf Institute and the Direct Manufacturing Research Center conducted an expert survey on current and future requirements on DM-technologies in order to identify the most important requirements and the companies' and AM-technologies' performance concerning these requirements. This enables the AM-industry to develop and pursue consistent technology strategies and to bundle available competences to effectively advance AM to DM.

The overall assessment of the general requirements shows that:

- The significance of all general requirements will increase in the future.

- All requirements are and will be more significant for machine manufacturers than for material suppliers.
- **High innovation ability** has the highest significance today, for both, machine manufacturers and material suppliers, and will be the most significant requirement in future.
- **Strong problem solving competences** currently have a relatively small significance, but its significance will significantly increase in the future for both groups.
- For machine manufacturers, a **continuous IT-support** has the largest deviation between current and future significance.
- For material suppliers, a **distinct customer orientation** will be crucial for the business of tomorrow.

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 processable shape memory alloys;
- Automated integration of AM-machines into existing production lines;
- Highly integrated AM-machines.

Especially with regard to these requirements, there is a need for action. According to the experts' assessment some requirements, such as a **build chamber volume** sized larger than 8 m^3 , are of minor significance, although these are basic prerequisites for the realization of a large number of application ideas developed for the aerospace and automotive industry.

In the future, many requirements might become critical if no technological advancements will be achieved.

All in all, the significance of the technology-specific requirements largely correlates with the technology's degree of performance across all considered technologies. As the significance of most requirements will increase, the vast majority of the requirements are likely to turn into critical requirements if no technological advances will be achieved.

4

Conclusion and Outlook

The study "Thinking ahead the Future of Additive Manufacturing – Future Applications" reveals future application ideas and innovation fields for AM-technologies. In addition, the study comprises current and future requirements to advance AM-technologies from Rapid Prototyping to DM-technologies.

For the aerospace, automotive and electronics industry, future scenarios were developed.

At first, the present study summarizes the Business of Today and the Business of Tomorrow for the aerospace, automotive and electronics industry, as these were identified to be the most auspicious application fields for AM. To describe the Business of Tomorrow, scenarios were developed for the aircraft and automotive production as well as for the electronics industry manufacturing equipment.

Based on the scenarios, ideas for future application of DM were identified.

The selected reference scenarios and the deduced future chances, risks and success factors were used as an impulse for product discovering. Against this background, ideas for future applications were developed using a systematic idea management. These were pooled to innovation fields and ranked according to their chances and risks.

For the most auspicious applications, the technical and economic feasibility have to be proved.

To enhance the penetration of AM in the three industries, particularly those innovation fields, which were identified to be the most promising, should be addressed in the future. Therefore, realization and implementation studies have to be performed by industry experts in cooperation with AM-experts. The object is to prove the technical and economic feasibility of the identified applications.

All in all, 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.

Requirements on DM-technologies were deduced from the innovation fields and validated in an expert survey.

From the developed innovation fields, requirements, which the identified applications impose on DM-technologies, were derived and validated within an expert survey. To promote the broad-scale implementation of AM, the technologies have to be developed according to the most important future requirements, such as process stability, build-up rates, availability of new materials and material properties etc.

Further proceeding in the project: Derivation of required technological advancements.

In future work, necessary advancements of existing DM-technologies with regard to the examined requirements will be outlined. The result is an innovation roadmap, indicating when the developed future applications can be manufactured as technological requirements will be fulfilled. This represents the synchronization of the Market Pull and Technology Push. The public study comprising these results will be published in summer 2012.

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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

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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.

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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)									

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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) $R_a > 10\ \mu m$								
b) $5\ \mu m \leq R_a \leq 10\ \mu m$								
c) $1\ \mu m \leq R_a < 5\ \mu m$								
d) $R_a < 1\ \mu m$								
4) Dimensional accuracy (average deviation in µm)								
a) < ± 50 µm								
b) ± 50 - 100 µm								
c) > ± 100 µm								

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	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								

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	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.

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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.

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