Thinking ahead the Future of Additive Manufacturing –

Exploring the Research Landscape

DMRC
DIRECT MANUFACTURING RESEARCH CENTER

HEINZ NIXDORF INSTITUTE
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Imprint

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Preface

Global warming, energy transition, population ageing and decreasing resources present us with immense challenges. In order to deal with these, we need fresh approaches, technological advances and clear implementation strategies. Our research strategy, “Fortschritt NRW” (engl. Progress NRW), therefore focusses on system innovations and change along the supply chain, incorporating ecological and social advances right from the beginning. Such comprehensive approaches work particularly well in networks with competent partners.

The Direct Manufacturing Research Center (DMRC) 2008 started out as such a network. DMRC is a joint project where University of Paderborn, partners from industry and the North Rhine-Westphalia Government conduct research into a technology that provides smart solutions for tomorrow’s production processes: Additive Manufacturing.

Additive Manufacturing enables many industries to speed up or even revolutionize their production processes. For example, lightweight production and functional complexity can help educe the consumption of resources for the process and the product itself, streamline manufacturing processes, make products more sustainable, simplify supply chains.

For Additive Manufacturing technologies to take the step into serial production, existing knowledge and skills need to be pooled, and projects initiated for the benefit of potential users. Broad application will only be successful if the transfer of research findings to industry is ensured.

This is the basis for the submitted study. Carried out by the Heinz Nixdorf Institute and DMRC, it is an analysis of the AM research landscape and the factors that make it such a success story. The study’s findings enable the DMRC and other research establishments to develop consistent and forward-looking research strategies.

DMRC’s partners benefit greatly from the center’s focus on application-led research, and the study is a major step towards establishing Additive Manufacturing as a way to deal with the challenges faced by society. It can therefore safely be said that the DMRC contributes significantly to the success of our research strategy, “Fortschritt NRW”.

Best regards

Svenja Schulze

North Rhine-Westphalia Minister for Innovation, Science and Research

Preface

Additive Manufacturing (AM) technologies have significantly evolved over the last decade. Engineers across several industries have been attracted by these technologies due to their potential to extensively transform the nature of manufacturing processes, e.g. by enabling “Freedom of Design.” Using AM especially for the creation of highly complex parts can be an economically viable alternative to conventional manufacturing technologies. Therefore, the aerospace industry is one of the leading industries in developing AM.

At Boeing, we are currently using AM-technologies to create production parts for many of our aircraft. With our world-class partners, we are continuously striving to expand the use of these technologies in a prudent and efficient way. In 2008, we became a founding partner of the Direct Manufacturing Research Center (DMRC) at the University of Paderborn in Germany. Here, we work with key technology suppliers and forward-thinking users who are dedicated to perform the transition of AM from an emerging to a production-rugged technology.

This process requires a strategic perspective: in particular, technology suppliers and research institutions need tangible feedback with regard to (potential) users’ requirements to focus their research. This is the starting point of the project “Research Strategies for Additive Manufacturing Technologies,” conducted by the Heinz Nixdorf Institute and the Direct Manufacturing Research Center. The goal is to develop promising research strategies to advance AM-technologies from Rapid Prototyping into dependable Direct Manufacturing technologies (DM) – the application of AM in series production.

To avoid redundancies in research, it is necessary to gain a sound overview on the current Additive Manufacturing research landscape. Especially research fields that are of high future relevance and are barely developed – the so called *white spots* – have to be revealed and addressed with utmost intensity in future research strategies. Together with the DMRC and its partners we strive to face the challenges that accompany this groundbreaking task. The present study is the fourth study conducted under the auspices of the Direct Manufacturing Research Center. It covers the Additive Manufacturing Research Map, develops a vision for the future of AM and deduces future-oriented, promising research strategies that can help to achieve this vision.

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

Best regards

Paul Pasquire

Vice President, Global Technology
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Introduction

The present study comprises results of the project “Research Strategies for Additive Manufacturing Technologies” performed by the Direct Manufacturing Research Center and the Heinz Nixdorf Institute, University of Paderborn, Germany.

Object of the project is the development of an Additive Manufacturing (AM) Research Map and the deduction of success factors for future research, concurrently exploiting future success potentials identified in the preceding project “Opportunities and Barriers of Direct Manufacturing Technologies for the Aerospace Industry and adapted others”.Therefore an analysis of research institutes and research fields is carried out that allows identifying promising fields of activity.

Goal of the project are consistent, future-oriented research strategies that allow exploiting future potentials. These strategies enable research institutes to bundle their competences to consequently pursue projects with maximum benefits for potential users of AM.

The results of the project are published in one public and one confidential study, presenting the Additive Manufacturing Research Map and showing up success promising combinations of (research) activities to advance AM and to increase its industrial penetration. The public version comprises an overview of the project results; the confidential version encompasses all results gathered in the project and is accessible for DMRC partners.

The results of our preceding project were published in three studies, focusing the analysis of AM’s today’s business as well as strategic product and technology planning. An electronic version of these studies is available on the DMRC website www.dmrc.de/en.

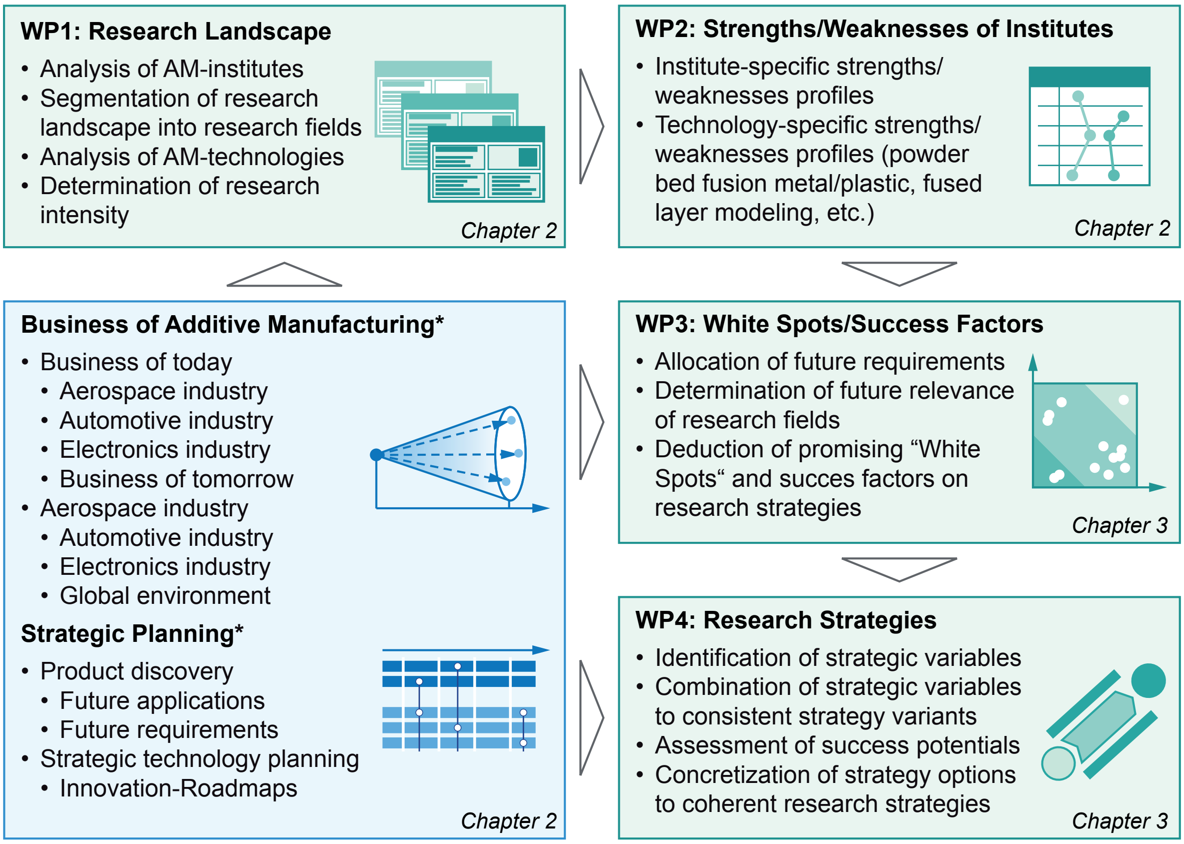
Proceeding in the Project

The present project is structured into 4 work packages, see the green colored work packages in figure 1. A number of impulses for this project were set by the preceding procect, blue colored in figure 1.

In **work package 1**, the Additive Manufacturing research landscape is analyzed to answer the following questions:

- Which are the main research institutes in AM?
- How is the research landscape segmented?
- What are the research fields that have to be investigated to advance AM towards Direct Manufacturing (DM), and thus to increase its penetration?
- What is the degree of research intensity in the determined research fields?

For this purpose, the research intensity of selected AM-institutes within defined research fields is determined as part of a survey. Based on these findings, an AM Research Map is developed.



* Part of preceding project "Opportunities and Barriers of Direct Manufacturing Technologies"

Figure 1: Proceeding in the project

Work package 2 covers the following questions:

- Which research fields are intensively investigated and which are hardly occupied?
- Which are technology-specific strengths and weaknesses in the research landscape?

To answer these questions, institute-specific and technology-specific strengths and weaknesses profiles are developed. This allows identifying research gaps.

However, research gaps do not exactly correspond with the research demand. To determine the research demand, the following questions are answered in **work package 3**:

- Do the determined research initiatives address future requirements?
- Which are the *white spots* – research fields of high future relevance that are hardly being explored in the research landscape?
- Which are enabling success factors for future research strategies?

To answer these questions, additionally the results from the project "Opportunities and Barriers of Direct Manufacturing Technologies" are used, see the blue colored work package in figure 1. In this project, future requirements on DM-technologies were deduced; the performance of selected technologies was assessed regarding these requirements as part of expert surveys.

To deduce the research demand in the present project, first of all the future requirements are allocated to the research fields. Based on this, the considered technologies are assessed regarding their performance concerning these future requirements. Instead of committing to the fields with a low performance prematurely, it is important to take into account the relevance of the research fields, meaning whether research in the respective fields does align well with the future requirements. Based on this, *white spots* and enabling success factors for future research strategies are deduced.

In **work package 4**, implications on future research strategies are deduced. Thereby, both – *white spots* and success factors – represent *strategic variables* that can have *different characteristics*, meaning strategic levers with different, conceivable positions the company can adjust in a strategy. The strategic variables' characteristics are combined to consistent and unique combinations that basically represent the research strategies. Therefore, the following aspects are addressed:

- Which are strategic variables (technology-specific and organizational) and conceivable characteristics for future research strategies?
- What are consistent strategies (consistent combinations of the characteristics)?
- What are success potentials of these strategies?
- Which strategies are being pursued in the research landscape?

Technology-specific levers specify which research fields should be addressed in the research/technology development. Organizational levers specify the required infrastructure for increasing the output, in terms of requirements on the necessary infrastructure and activities. These are combined to consistent research strategies.

This study comprises an excerpt of the results derived from the project and is publicly accessible. An electronic version of the study will be available soon on the DMRC website www.dmrc.de/en.

Proceeding in Study

The present study "Analysis of the Additive Manufacturing Research Landscape" presents the results of the project mentioned above. It identifies strategic variables and comprises a combination of these strategic variables to consistent strategy variants. The main results emerged from several workshops at the Heinz Nixdorf Institute, Paderborn, Germany and at Boeing, St. Louis, USA. In addition, the institutes that were considered in a detailed analysis supported the project by providing specific background information on the institutes' profile and research activity. Furthermore, a total of over 150 experts contributed to the results by providing their expertise in the expert survey on the Future Relevance of AM-research. The study comprises 4 chapters.

The **first chapter** gives an overview of Additive Manufacturing – the development from its beginning until now. In addition, it presents a section on the worldwide, increasingly growing awareness of AM-technologies and their potential, which is basically expressed by various research initiatives dedicated to advance AM further. In addition, we provide a brief overview on the preceding project conducted by the Heinz Nixdorf Institute and DMRC.

The **second chapter** outlines the procedure used for the development of the AM Research Map. This includes an analysis of research institutes, AM-technologies, the segmentation of the research landscape, and the determination of the research intensity in resulting research-field/technology-combinations (work package 1). Based on the results, institute-specific and technology-specific strengths/weaknesses-profiles are deduced (work package 2).

The **third chapter** outlines the procedure for developing *ideal, consistent* research strategies. In our understanding, a strategy is a way/plan for achieving a vision. To ascertain a research strategy is aligned with future market demands, we revert to the results gained in an expert survey on the Future Relevance of AM Research. This allows – apart from the determination of the future relevance – the deduction of so called *white spots* – those research fields that are highly relevant for a broad penetration of AM, but insufficiently addressed in current research projects. Finally, deduced success factors for future research strategies are presented (work package 3). On this basis, strategic levers are deduced and combined in a consistent way to develop strategy variants. Correspondingly, the chapter analyzes the strategies of the considered institutes and presents a Strategy Map, indicating which strategies are pursued by which institutes and which of the consistent strategies are not occupied in the research landscape (work package 4).

The study concludes with a **conclusion** emerging from the project's results. In addition, it provides an **outlook** on further investigations about the future of Additive Manufacturing performed by the Heinz Nixdorf Institute in collaboration with the DMRC.

Participating Companies/Institutions

- Additive Manufacturing and 3D Printing Research Group, University of Nottingham
- Additive Manufacturing Research Group, Loughborough University
- Advanced Manufacturing Center, University of Texas at Austin
- Benteler International AG
- Blue Production GmbH & Co. KG
- BMW AG
- The Boeing Company Corp.
- Direct Manufacturing Research Center
- Division Production engineering, Machine design and Automation, KU Leuven
- Eisenhuth GmbH & Co. KG
- EOS – Electro Optical Systems GmbH
- Evonik Industries AG
- Fraunhofer Institute for Manufacturing Technology and Advanced Materials
- Fraunhofer Institute for Laser Technology
- Harvest Technologies Corp.
- Heinz Nixdorf Institute, University of Paderborn
- Honda Motor Co., Ltd.
- Huntsman Advanced Materials GmbH
- inspire irpd – Institute for rapid product development
- LEGO Systems A/S
- Met-L-Flo Inc.
- microTEC GmbH
- National Institute of Standards and Technology (NIST)
- Paramount Industries, Inc.
- PHOENIX CONTACT GmbH & Co. KG
- Rapid Prototyping Center, University of Louisville
- Rapid Technology Center, University of Duisburg
- RMB Products, Inc.
- Siemens AG

- SLM Solutions GmbH
- Stratasys, Inc.
- Stükerjürgen Aerospace Composites GmbH & Co. KG
- Technical University Hamburg-Harburg: Institute of Laser and System Technolgies & Laser Center North
- UNITY AG
- University of Erlangen-Nuremberg, Collaborative Research Center 814 – Additive Manufacturing
- University of Paderborn
- University of Siegen
- University of Sheffield
- Weidmüller Interface GmbH & Co. KG
- Witte Automotive GmbH
- W.M. Keck Center for 3D Innovation, University of Texas at El Paso
- and many other experts who participated in the expert surveys.

Reading Instructions

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

Management Summary

The present study yields an overview of the results of the project "Research Strategies for Additive Manufacturing Technologies", comprising three parts: *Overview on Additive Manufacturing*, the *Analysis of the Additive Manufacturing Reseach Landscape* and the *Development of Research Strategies*.

The first part gives a concise overview on the development of AM-technologies, the actual developments, comprising current initiatives and up-coming trends. Additionally, the preceding project is presented – lining out future scenarios, applications and innovation roadmapping of required advancements. The required advancements shows up which research fields need to be explored for the future penetration. In a next step, the current research activities and intensity – the state-of-the-art research landscape was analyzed. The resulting AM Research Map indicates the research activity and intensity of selected AM-institutes in defined research-field/technology-combinations. This allows deducing research fields that are being intensively investigated and those that are hardly examined in current research initiatives. Merging these results with the future relevance of research fields ascertained as part of a survey, *white spots* and enabling success factors for future research strategies emerge. Taking these into account, consistent research strategies are developed and the prevailing research strategies in the analyzed research landscape are captured. Both are merged in a Strategy Map.

Overview on Additive Manufacturing

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

The analysis of today's AM business and current initiatives indicates that AM is definitely a disruptive technology which is progressively permeating diverse markets. The technology is certainly capable to trigger major upheavals reshaping supply chains and business models over the next decade. A lot of industries are seeking for opportunities how to capitalize on the benefits AM provides, e.g. the "Freedom of Design". New industries progressively draw their attention to AM's potential. As well, global research initiatives funded by different governments spark new impulses in the research landscape. Established and newly founded research centers, e.g. in the UK, the US or Germany are continuously striving to close gaps in the research landscape and to transfer the research results into tangible outcomes for the industry. However to reach this, consistent and demand-oriented research strategies are needed.

Successful research strategies are based on a visionary look into the future.

Future requirements: process stability, certification, design rules and on-line control processes

To ensure future relevance and success of research strategies, these need to be based on a visionary look into the future. A visionary sight into the future occurred in the previous project "Opportunities and Barriers of Direct Manufacturing Technologies". Relevant branches and future applications for AM were identified and resulting requirements on significant future advancements of AM-technologies were derived. Based on this, technological implications were deduced, e.g. the need for the development of design rules or increasing the process stability of AM-processes, certification and processes for the control of part quality during the production processes.

Additive Manufacturing Research Map

The AM Research Map provides an overview of current research activities across different research fields.

To delineate the need for research activity, the research landscape was analyzed. As a results, the Additive Manufacturing Research Map was created. The data for the development of the AM Research Map was collected in a survey conducted in 2012. A number of conclusions emerged from the Research Map. For instance, just a few institutes focus on cross-technological research fields, e.g. the development of design rules and standards; the research intensity is medium. Other research fields, e.g. material research, are intensively investigated. Thereby, the research landscape reveals the strengths and weaknesses of the analyzed research institutes and shows up research fields that are hardly occupied in the analyzed research landscape.

An outstanding research intensity is prevalent in the following research fields:

- Mechanical Properties,
- New Materials,
- Material Quality,
- Microstructure Manipulation and Material/Powder Generation.

Research fields with a rather low research intensity are especially:

- Supply Chain Optimization,
- Machine Costs,
- Process Automatization,
- Material Costs and Recycling Costs.

Concurrently, conclusions emerge for technology-specific research intensity, differentiating four categories of technologies.

- **Fused Layer Modeling Technologies:** The research activity is low. Just a few institutes are investigating in a few research fields, e.g. in material quality or mechanical properties.
- **Powder Bed Fusion Plastic Technologies:** The research activity is rather high: on average four institutes are working in one research field, e.g. in the research fields new materials and mechanical properties.
- **Powder Bed Fusion Metal Technologies:** The institutes indicate the highest research activity in total, distributed over all research fields. On average, more than six institutes are involved in one research field.
- **Polymerization Technologies:** For these technologies, the lowest research activity of all technologies prevails. Especially noteworthy is the comparably high research intensity in the field of electric properties, indicated by one institute.

Development of Research Strategies

Highly important and barely developed research fields need to be revealed.

To align future research strategies with the research demand and to identify crucial technological levers, the research fields that are of importance in the future and are barely developed at the same time – so called *white spots* need to be revealed. Therefore both, activity and intensity of today's research have to be contrasted with the future relevance of the research fields. Once technological levers are determined, it is important to take into account resulting organizational levers that are mandatory to realize the technological levers. These are called enabling *success factors*.

Highly relevant research fields with a short- or mid-term time of relevance, indicate an immediate need for action for the future penetration of AM. The experts' assessment shows that:

- The vast majority of the research fields are of high or at least medium relevance.
- Investigations on material quality, functional materials and new materials are assessed to be of outstanding relevance for the industry in the category *material research*.
- In *product research*, design rules, part tolerances and lightweight structures are highly relevant.
- For the other categories, for instance research on process tolerances and integration of AM into existing manufacturing processes was rated to be significant.

White spots and success factors give hints on strategic levers.

Merging the relevance of the research fields with the technologies' performance and the research intensity, *white spots* were deduced. For instance, the research fields *process automatization* and *design rules* were determined as *white spots* and should be considered as technological levers in future research strategies. Research fields, such as *new materials*, are critical for the future penetration of AM as well. Here however, the research intensity is already high.

Based on the *white spots*, *success factors* enabling the technological levers were deduced. For instance, research in the mentioned *white spots* could significantly benefit from e.g.:

- Stronger interconnection of intitutes within the research landscape and
- Closer integration of companies along the value chain.

Ten consistent, success promising and future relevant research strategies were developed.

By adding the competition arena to the research strategies, a Strategy Map was created.

These results enable a research institute to revise its currently pursued strategy and to find a success promising and future relevant strategic position in the research landscape. To develop consistent strategies, many strategic aspects deduced from the *white spots* and *success factors* were taken into consideration. Based on this, ten consistent, and thus resource-efficient strategy variants were developed, ranging from a *Fundamental Scientist* to a *Problem Shooter*. Once the strategies are developed, the competition arena needs to be analyzed. In a subsequent step, the developed strategies are contrasted with the strategies the analyzed institutes cur-

Different strategies are discernible in the research landscape.

rently pursue. The result is a Strategy Map. At a first glance, it can be stated that:

- The institutes are well distributed around the ten consistent strategy variants.
- None of the institutes pursues a completely consistent strategy.

Each institute can assess the ten strategies concerning attractiveness and the effort required to perform a shift. A question that arise from these results is how can we use this diversified distribution of the institutes' strategies to generate synergy effects in research?

All in all, the results of the study should inspire to think about how we can design the AM research landscape in terms of technological levers – basically represented by the highly relevant research fields for each technology, as well as in terms of organizational levers, in terms of the required infrastructure for enhancing the technological levers.

A lot of research work is beeing done for advancing AM.

The analysis of the research landscape shows that there are many research initiatives, many institutes dealing with AM, and a number of different strategies are discernible. Hence, we are doing a lot. However, some research fields are repeatedly explored; this costs time and money, and does not necessarily contribute to advance the technology. Moreover, there still are some *white spots* in the research landscape that could be addressed more extensively, and there still is potential regarding the infrastructural levers, just to name a few examples:

Some potentials are still untaped to leverage a more beneficial research output.

- What if we would, for instance, realize synergy effects within the research through a stronger interconnection in the landscape or
- What if we would collaborate more closely along the whole value chain?

Doing so – we are sure – we definitely could leverage a more beneficial and tangible research outcome for the industry, and thus accelerate the penetration of AM.

1

Overview on Additive Manufacturing

This chapter provides an overview on Additive Manufacturing. Chapter 1.1 outlines the development of AM from its beginning until now. Chapter 1.2 briefly describes actual developments, addressing current initiatives and up-coming trends. Chapter 1.3 presents the preceding project that was conducted by the Heinz Nixdorf Institute in collaboration with the DMRC – lining out future scenarios, applications and innovation roadmapping of required advancements.

1.1 What is Additive Manufacturing?

AM is the layer-wise creation of parts.

Additive Manufacturing (AM) technologies refer to a group of technologies that build physical objects from Computer Aided Design (CAD) data. The main difference between traditional and AM-technologies is that parts produced via AM are created by the consecutive addition of liquids, sheet or powdered materials in ultra-thin layers, instead of removing material to generate a desired shape which is common to traditional technologies such as milling or drilling.

Additive Manufacturing has been around since the 1980s, and has many common names, involving rapid manufacturing, direct manufacturing, 3D-printing, rapid tooling and rapid prototyping. We consider AM as the umbrella term for additive technologies; the terms direct manufacturing, rapid tooling and rapid prototyping refer to the application of AM.

At an early stage, AM-technologies have been applied to quickly create physical prototypes using resins and polymers. The term Rapid Prototyping refers to this kind of applications. Today AM-technologies are still used in product design and development processes in order to create haptic models and functional prototypes for checking form, fit and function. As the technologies have been developed further, they were also used for producing injection molding tools (Rapid Tooling) [GRS10], [Geb12]. Progressively, AM finds its way into the production of end-use parts in many industries as well, which is expressed by the term Direct Manufacturing (DM).

In addition, no matter for which purpose AM is used, many different AM-technologies are available: the foundation was laid by Stereolithography and Laser Sintering technology. Today, two main streams can be distinguished: laser-based and nozzle-based technologies.

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

Using nozzle-based processes, e.g. Fused Layer Modeling (FLM), wire-shaped thermoplastic material is melted and extruded through a nozzle. The nozzle moves along the contour of the layer; the extruded material bonds with the previous layer through thermal fusion. Laser-based processes, e.g. Laser Sintering, use the laser energy to form each layer. The material powder (e.g. metal, plastic, sand) is applied in a thin layer on the part. A laser solidifies the individual layer by sintering, melting or laser light solidification [Geb12], [GRS10].

Due to its layer-wise principle, AM enables the production of individually shaped parts whose production was previously inconceivable, and thus AM is already today in the clear technological vanguard when it comes to “Freedom of Design”. AM definitely does have the potential to unleash a new wave of product innovations. But which tremendous opportunities will this technology provide in the future? At all, which benefits could be yielded if we advanced AM even further?

1.2 Status Quo, Current Initiatives and Future Trends

Within the last years, AM-technologies are about to advance from Rapid Prototyping to industry-relevant manufacturing technologies. At the forefront of the development stands the industrial demand for a highly flexible, individual and economic production technology for end-use parts. Seen in this light, AM’s potential does not only relate to the capability to revolutionize and accelerate product development processes in various industries, and to create value along the corresponding supply chains; more extensively, AM has the potential to realize business models that were inconceivable before.

AM market has grown by 18% in average every year.

The evolution over the last decade demonstrates this process – the market has grown by 18% average every year; the current volume is estimated to be about $1.3 billion [THW11-ol], [Woh11]. Worldwide, the awareness of AM’s potential is increasingly growing. Governmental institutions, research institutes and practitioners recognize the need for action and strive to develop AM further in different ways. Technology suppliers, e.g. machine manufacturers and material suppliers, respectively work on the development of (new) processes and materials. AM has started to take off.

Industrial Development of Additive Manufacturing

Companies have identified AM as a valuable technology for their production processes with promising future potentials as well. As indicated in figure 1-1, the number of AM-systems sold per year has been continuously growing.

Aerospace industry is one of the leading industries applying AM.

Many of them established their own research centers or labs and spend a sizeable amount of their R&D budget on advancing AM. One of the leading industries in applying AM for production of end-use parts is the aerospace industry. Boeing already uses additively manufactured parts within their airplanes, especially where lightweight parts, concurrently providing high stiffness and increased part functionality, are needed. In addition, the production of complex geometries in low numbers which is common for the aerospace industry, makes AM economically attractive for being used in aircraft production. To increase exploitation of AM’s potential, Boeing is either involved in or leads several research centers around the world, and takes part in different committees and organizations dedicated to AM. Other globally acting companies like Siemens or Evonik are involved in AM research as well. For example, the chairman of the RM Platform – The European Collaboration on Rapid Manufacturing – is provided by Siemens.

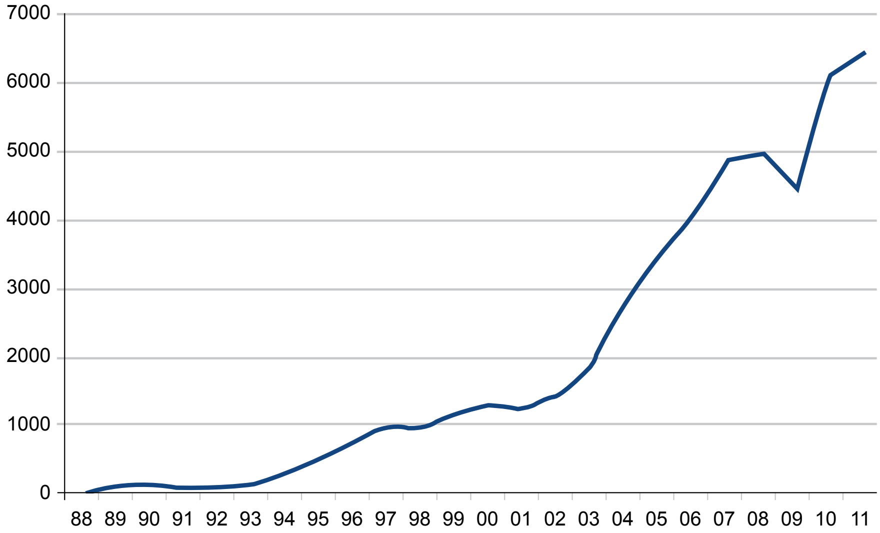


Figure 1-1: Additive Manufacturing systems sold per year [Woh12]

Medical industry is using AM for highly individualized medical devices and implants.

The medical industry has adopted AM for selected applications as well, e.g. for producing highly individualized medical devices and implants, like hearing aids or dental prostheses. Fortunately, new industries are increasingly becoming aware of AM's potential and new applications arise. Particularly creative industries and toy/fun industries are progressively developing innovative business models which result in either modified or even completely new supply chains. The major benefit is mass customization, meaning the personalization of products. A well-known business model is 3D-printing of World of Warcraft® Avatars on www.figureprints.com (©2004 Blizzard Entertainment, Inc.). Furthermore, AM is being applied in some capital goods industries as the armament, automotive, electronics and further more. As a conclusion, AM is expected to enable new business models and re-configured supply chain in many industries.

Nevertheless, there are still a high number of open research fields to be investigated in order to tap the full potential of AM. Even more, the transfer of research results into practical implications is necessary.

Further Trends – Main Drivers for Additive Manufacturing

Additive Manufacturing opens up many opportunities to cope with different challenges in many industries, as already discussed above. Trends and challenges facilitating AM and vice versa are provided in the list below:

- Integrated functionality, intelligent systems: Functionality can, for instance, be realized by integrating acoustic and thermal insulation into parts or by embedding entire sensor/actuator systems, including electronic wiring and connectors into a part. This can contribute to realize self-optimizing parts [GEW13].

- Light-weight structures: AM allows the production of light-weight parts which massively cuts down material consumption, but concurrently guarantee the desired part stiffness [GEW13].

- Sustainable production: AM is heralding a new dimension of sustainable production, as it does in fact have a number of sustainable advantages. AM can mitigate consumption of raw materials within in the product and production process itself; manufacturing processes can be streamlined; lower product lifecycle costs can be realized through higher product efficiency via lightweight and functionally integrated structures; moreover, value chains can be simplified (distributed production, production just-in-time etc.) [GEW13].

- Energy efficiency: In the era of natural energy scarcity, energy efficiency is the major point on the agenda of producing companies. Many of AM's capabilities which contribute to a sustainable production, concurrently influence the environment in a positive way. Environmental impacts are reduced, which adds value to industrial business [GEW13].

- Neo-Crafting, Mass customization, personalization, individuality: Hand-crafted parts are on the rise again, as people are striving for individuality. AM is able to realize parts as individual and special as hand crafted. In this "make-it-yourself" logic, economies of scale do no longer play a role, as any individual part is equally complex to produce. The motto here is: "N = 1" realized by "Ctrl + P" [Tre13a-ol], [Tre13b-ol].

- Co-Creation: AM-technology is set to make a huge impact on design, development and manufacturing processes. Cloud Production is often named as fields of research that will significantly gain in importance for technology suppliers, but producing companies as well. Co-creation involving different parties along the AM value chain may be an appropriate way for a collaborative development of new processes and materials, and the creation of products to be manufactured additively [GEW13].

- Bio-printing: Bio-printing is an upcoming research and engineering area. Parts are printed by the deposition of biological material. This kind of printers are at the development stage in research institutions; at this moment, these printers do not provide the required speed and accuracy. However, the long-term goal is to advance the technology for the production of organs or entire organisms [Wis13-ol].

- Food Printing: 3D-printers could be applied to print food for instance on space missions; NASA is already investigating in this kind of applications. Experts also expect great commercial potential for this technology resulting from the possibility to create customized food and meals tailored to a person's nutritional needs [Par13a-ol].

- Nano-printing: Nano-printing refers to the creation of parts as small as a grain of sand. For instance, it is used to build scaffolds to promote the regrowth of damaged bones [Bbc12-ol].

- Besides the professional research and industrial machines, low-cost 3D-printers are in the ascendancy, as indicated in figure 2-1 [Woh12, S.218ff.]; these are increasingly helping to create visibility of additive technologies for the industry, facilitating access to the technology for inventors, entrepreneurs, researchers, do-it-yourself enthusiasts, hobbyists etc. [Woh12]. Many machine manufacturers produce machines for hobby and home users for less than 1.000 €. In 2011, ca. 8.000 professional AM-machines have been sold; in comparison, more than 23.000 low-cost-machines were sold. Possible fields of application for these low-budget-printers are teaching and education in schools or universities – to familiarize young engineers, designers and hobby-scientists with the possibilities of AM-technologies. This creates a bigger AM-community which will lead to more involvement in AM worldwide [Vil12-ol].

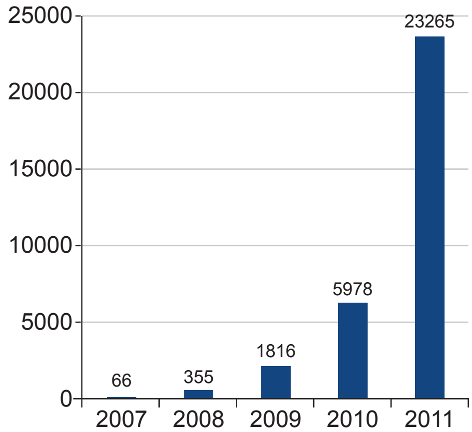


Figure 1-2: Low-cost systems sold per year [Woh12]

Current Research Initiatives for Additive Manufacturing

UK, USA and Germany are leading states regarding initiating programs for research in AM.

Striving to close these gaps, governments around the world are continuously launching programs fostering research on AM and the transition of the research output into tangible outcomes for the industry. At this moment, UK, USA and Germany are leading states regarding initiating programs for research in AM, which is reflected by the number of publications worldwide, see figure 1-3. Examples for those programs are the Catapult program in the UK, the foundation of the Direct Manufacturing Research Center (DMRC) and the CRC 814 in Germany, or the newly founded NAMII Institute in the US. All of these efforts converge and aim at advancing AM to a production capable technology.

The EPSRC Centre for Innovative Manufacturing in Additive Manufacturing (UK) is hosted by the University of Nottingham since July 2012, in a close partnership with Loughborough University. The head of the center is Prof. Richard Hague. The EPSRC Research Council provided a funding amount of £4.9 million; participating companies contributed another £3.2 million. The main focus of the research work is the production of “ready assembled” products consisting of multiple materials for a wide range of industries [Lou13-ol].

The Direct Manufacturing Research Center (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 – the application of AM in series production. In 2008 the DMRC started its research work at the University of Paderborn, Germany. Eight professors constitute an interdisciplinary research center performing research on the transition of AM towards DM. The federal state of North Rhine-Westphalia and the involved companies contributed 11 € million for the time frame from 2009 to 2016 to support the research work in Paderborn [Dmr09-ol].

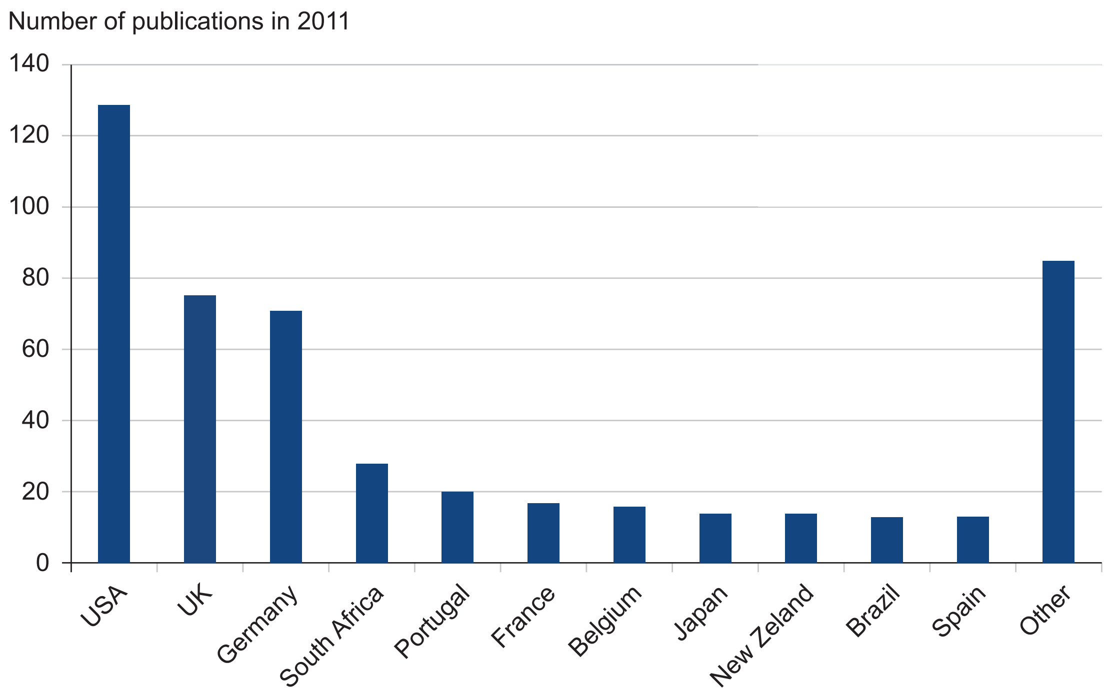


Figure 1-3: Number of publications dealing with Additive Manufacturing [Eco12-ol]

The CRC 814 – Additive Production is a collaborative research center at the University of Erlangen-Nuremberg. Under the suspicious of Prof. Dr.-Ing. Drummer, 35 researchers are working on a better understanding of the behavior of powders within the process. This will be the basis for the development of new optimized powders as well as the optimization of AM-machines and process parameters. The CRC 814 was established in July 2011 with a budget worth of 7.3 € million and 1.4 € million respectively contributed by the German Research Foundation (DFG) and the federal state of Bavaria [Fau13-ol], [Sfb13-ol], [Fau12].

The NAMII – National Additive Manufacturing Innovation Institute, located in Youngstown, Ohio, is a pilot institute for a partnership between academia, industry, government and workforce development agencies. Currently the NAMII consortium includes 40 companies, 9 research institutes/universities, 5 community colleges and 11 non-profit organizations [Ley12-ol]. The pilot institute strives to combine basic research with product development, concurrently fostering education in AM: training for engineers, designers and producing companies. The federal government provided $30 million initial funding for NAMII's start in August 2012; additional $40 million were contributed by the consortium [Amp13-ol], [Ncd12-ol], [Ley12-ol].

Goal of the project "Research Strategies for Additive Manufacturing Technologies"

Goal: Bundling efforts / research work and to performing research projects with maximum benefits

These deliberations underline that great efforts are undertaken to advance AM. However, we believe that we still have a long way to go to tap the full potential of AM and before AM becomes ubiquitous. The next logical step should be to bundle the efforts/research work effectively and to consequently pursue research projects with maximum benefits for potential users of AM-technologies. This requires consistent and demand-oriented research strategies.

The study analyzes the AM research landscape and deduces research demand.

This is the starting point of the study conducted by the Heinz Nixdorf Institute in close cooperation with the DMRC. The study analyzes the Additive Manufacturing Research Landscape and presents an overview on the Additive Manufacturing Research Map. As part of surveys, the research intensity of selected research institutes within the defined research fields as well as the (future) relevance of the research fields were assessed. By contrasting the relevance with the research intensity, highly relevant research fields that however are not addressed so far are identified. Based on this, the study deduces success factors for success promising AM research strategies and shows up consistent strategy variants. The outcomes of this study enable research institutes to identify relevant and (future) promising positions in the research landscape.

Significant impulses for the present project were provided by the preceding project which was also conducted by the Heinz Nixdorf Institute and the DMRC. The project is presented in the next section.

1.3 Opportunities and Barriers of Direct Manufacturing Technologies

Future influences for an increase in market relevance of DM were outlined.

In the project "Opportunities and Barriers of Direct Manufacturing Technologies", future influences spurring an increase in market relevance of Direct Manufacturing (DM) technologies in the aerospace, automotive and electronics industry were outlined, 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, were carried out. This enables material and technology suppliers of the DMRC to develop the technologies into the right direction; in addition, they can significantly benefit from the strategic planning of future applications, as it serves as an incentive for their customers to use AM-technologies extensively.

The results of the project were published in three “Thinking ahead the Future of Additive Manufacturing“ studies:

- Analysis of Promising Industries [GEK+11],
- Future Applications [GEW12],
- Innovation Roadmapping of Required Advancements [GEW13].

The third study encompasses an overview of the project and an extract of the project’s overall results, comprising three elements: *Additive Manufacturing Business* and the symbiotic incorporation of *Strategic Product Planning* and *Strategic Technology Planning [GEW13]*.

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

1.3.1 Additive Manufacturing Business

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

The analysis of today’s AM-business indicates that AM is swiftly growing in significance for many industries as it offers great possibilities to accelerate innovation, compress supply chains, reduce material and energy usage, and waste. As indicated in figure 1-4, a lot of industries are seeking for opportunities how to capitalize on the benefits AM provides, e.g. the “Freedom of Design”. New industries progressively draw their attention to AM’s potential.

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

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

Figure 1-4: *Overview on industries using Additive Manufacturing [GEK+11] (pictures courtesy of: see picture credits on page 137)*

1.3.2 Strategic Product Planning

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

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

The selected reference scenario for the aerospace industry – the most probable scenario with the highest effect on the future aircraft production – describes a future, where with regard to the global environment Europe sets the pace in a globalized world. The future aircraft production is characterized by individual customization of aircraft which fosters the application of AM-technologies. In this world, many manufacturers jumped on board and have been increasing their investments into AM-technologies. Due to the successful part implementation, AM-parts started to be associated with high performance and high quality. Success in this future necessitates general ground rules for the design of secondary aircraft structures, systems etc. for AM-technologies that need to be flowed down to suppliers. Figure 1-5 visualizes the scenario [GEW12].

Figure 1-5: Visualization of the reference scenario for the aircraft production “Individual Customization Fosters Additive Manufacturing Technologies“ [GEW12] (pictures courtesy of: see picture credits on page 137)

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

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

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

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

27 innovation fields, comprising 120 ideas, were identified.

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

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

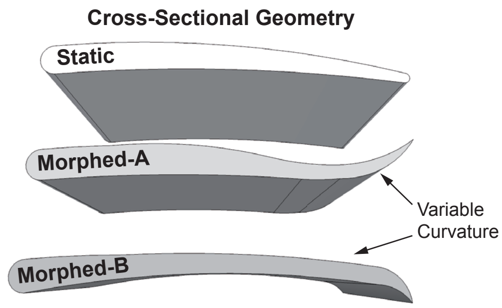
- **Morphing Structures** describe applications which are designed as one part that is adaptable in its shape in response to its operational environment. Instead of changing the position of a static part by using actuators, the part itself can take continuous configurations of shape to enable specific functions/properties. Figure 1-6 shows an exemplary idea from this innovation field [GEW12].

Morphing Wings

Description

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

Draft



Advantages/Benefits

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

Disadvantages/Risks

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

Current Technical Solution

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

Type of Idea

☐ product update ☐ adaption ☒ innovation

Figure 1-6: Exemplary idea from the innovation field Morphing Structures: Morphing Wings

- **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 [GEW12].

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

- **Handling of Fluids** yields an overview of parts that focus on geometric adaption of pipes, valves, restrictors etc. to individual purposes. Depending on their application, these parts have to be improved, for example with regard to optimized exchange of thermal energy and gas distribution, critical strength properties, weight or space reduction [GEW12].

- **Optimized Tooling** includes the integration of channels into tooling parts to improve durability and resistance of tools. By applying AM-technologies, a more flexible way of arranging cooling channels can be achieved, as cross-sections of cooling channels can take any arbitrary shape. Thereby, uniform heat dissipation and quicker cooling processes can be reached [GEW12].

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

- **Functionally Integrated Parts** include application ideas which focus on embedding electronics (circuits) into all kind of geometries and on functional integration of different electronic devices into a single part, following the principle of the Molded Interconnect Devices (MID)-technology [GEW12].
- **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 [GEW12].

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

To align the technology development with current and future requirements and to effectively advance AM-technology into dependable DM-technology, the developed innovation fields were analyzed in detail to deduce requirements. The range of requirements covers technology and material-specific as well as general requirements. The vast majority of innovation fields necessitate a high process stability, certification, design rules and processes for the control of part quality during the production process, just to name a few [GEW12].

1.3.3 Strategic Technology Planning

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

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

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

Large deviations between the current and future significance arise for:

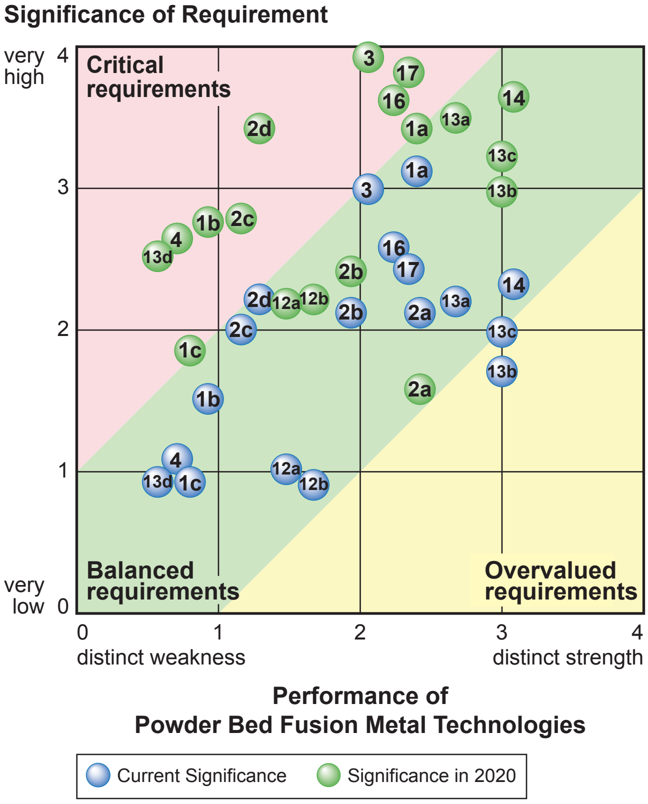
- Ability of AM-machines to process different types of materials within one job,
- Building up on 3-D surfaces,
- Provision of additively processible shape memory alloys,
- Automated integration of AM-machines into existing production lines,
- Highly integrated AM-machines.

However, although some requirements play a significant role for the realization of many applications, the experts only attach a subordinate significance to those. For instance, a large number of applications ideas from the aerospace or automotive industry, such as *Morphing Structures* or *Functional Body-in-White*, respectively, necessitate AM-machines with large build chamber volumes. The experts however do not expect a build chamber volume sized larger than 8 m³ to be relevant in the future [GEW12].

Contrasting the significance with the technologies' performance, the need for action was deduced for each technology. Therefore, each requirement is positioned in a significance-performance portfolio, as shown in extracts in figure 1-7. 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, balanced requirements – green area, over-emphasized requirements – yellow area [GEW12].

The technologies' degree of performance largely correlates with the requirements' significance today. However, the experts expect that the vast majority of the requirements will gain in significance. Hence, if the technologies' performance will not be advanced, these requirements will turn into critical requirements.

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



1. **Build chamber volume (V in m³)**
1a) V < 1 m³
1b) 1 m³ ≤ V ≤ 8 m³
1c) V > 8 m³
2. **Build-up rates (production speed at highest quality in cm³/h)**
2a) 1 - 10 cm³/h
2b) 11 - 40 cm³/h
2c) 41 - 100 cm³/h
2d) > 100 cm³/h
3. **High process stability**
4. **Integration of electronic circuits into additively manufactured parts**

⋮

12. **Processability of materials with AM-machines**
12a) Magnesium
12b) Shape memory alloys (SMA)
13. **Availability of new material properties**
13a) Fire resistance
13b) Thermal conductivity
13c) Electrical conductivity
13d) Self-healing properties
14. **Recyclability of materials**

⋮

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

Figure 1-7: Extract from significance-performance portfolio for Powder Bed Fusion Metal Technologies (e.g. Selective Laser Melting)

Some requirements, e.g. build-up rates > 100 cm³/h, are already considered as critical today. These requirements indicate required research areas, as these could promote AM-technologies in the future [GEW12].

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

The amount of research required to meet a requirement sufficiently strongly depends on the requirement itself as well as on the technology. For instance, an adequate availability of self-healing properties requires more effort in development than increasing process stability to a sufficient level; high process stability necessitates less research effort for powder bed fusion plastic technologies than for corresponding metal technologies [GEW12].

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

As part of a second survey, the point in time when the selected requirements are expected to be fulfilled by selected AM-technologies was revealed. The results were used to develop innovation roadmaps indicating when from the experts' point of view selected will be fulfilled, see example in figure 1-8. The overall assessment shows that advancements on fulfilling the technology-specific requirements are expected to require higher effort than the fulfillment of material-specific and general requirements. For instance, a database containing material properties and design rules are assumed to be available before 2016. In contrast, AM-machines with a significantly larger build chamber volume and higher build-up rates are expected to become available in 2025 at the earliest [GEW13].

Innovation roadmaps: Sophisticated tool for strategic product and technology planning

The innovation roadmaps are a sophisticated tool for strategic product and technology planning, as they allow aligning the technology development with current and future requirements. Moreover in these roadmaps, conceivable future applications can be positioned orthogonally at the earliest possible realization date of the requirements that need to be fulfilled. Thereby the roadmaps indicate when the applications can be realized as the technology will have reached the required performance [GEW13].

1.3.4 Research Fields of Interest

In addition to the assessment of the requirements, both surveys asked the experts to indicate fields of research and action that are of great importance for them within the context of AM. In the following section, frequently mentioned research fields are shortly described [GEW13].

New materials and qualification of existing materials for AM are expected to increase AM penetration.

- **Material Research:** Research on new materials and material properties is indicated as an action field of great importance. New materials as well as qualification of existing materials for AM are expected to increase the capabilities of AM-technologies, and thus to expand the technologies' penetration in industrial application. This counts for the development of new materials, like technical thermoplasts, natural and organic materials, bio-compatible and bio-degradable materials, nanomaterial, or ceramic, or new properties, like transparency, thermal (fire) and electrical resistance and isolation properties. Moreover so-called hybrids – bonds between metal and plastic components with electro-mechanical functions for e.g. electronic components, but also metal powder mixtures – are other fields of interest.

- **New/Advanced AM-Technologies:** The development of new/advanced AM-machines is indicated to be highly important, e.g. machines with multiple lasers. One challenge AM faces is multi-material processing, meaning the usage of several materials on the same machine. Plug and play machines are point of interest for the usage in remote areas, oil rigs, third world countries or naval ships. Furthermore, the participants indicated the interchangeability of process parameters between different AM machines (of one category) as an important field of action.

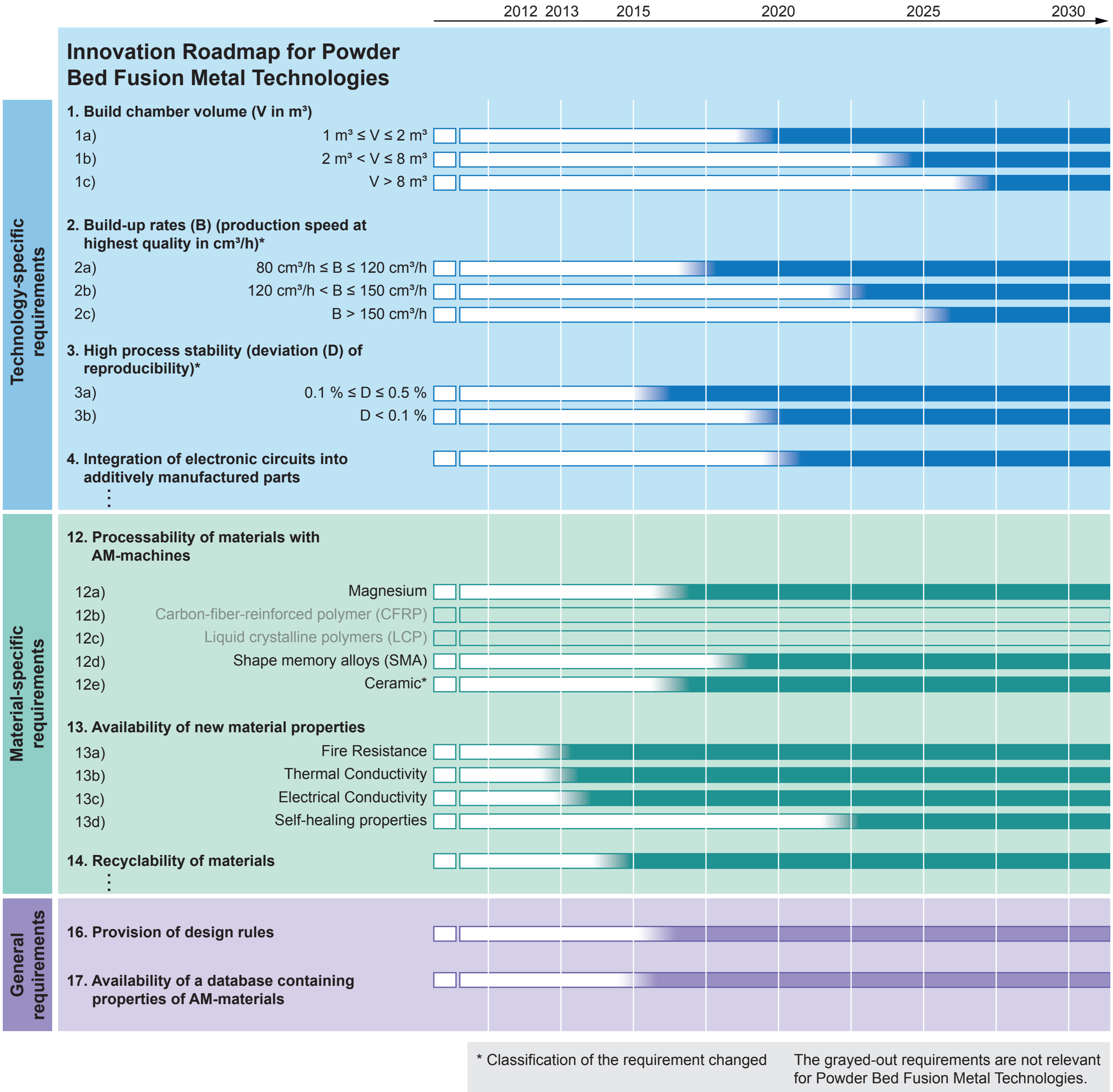


Figure 1-8: Extract from the Innovation Roadmap for Powder Bed Fusion Metal Technologies (e.g. Selective Laser Melting)

- **Process Optimization:** Process optimization regarding robustness, reproducibility, machine reliability, reduction of costs etc. is named as an important field of action. In addition, pre/post processing cannot be optimally performed today. Other aspects are process automatization, optimized data preparation, real-time process monitoring and control. Self-monitoring and self-optimizing processes are indicated to be the next evolution step in AM.

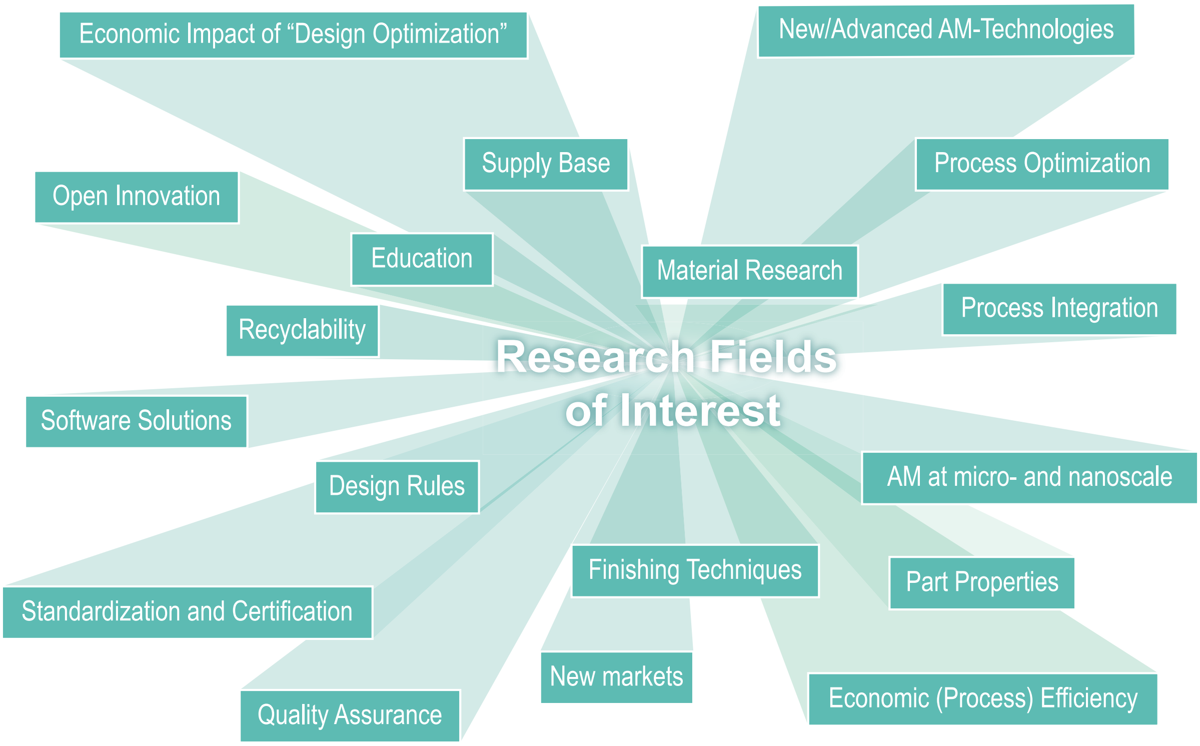


Figure 1-9: Overview on research fields of interest (summarized aspects from both expert surveys conducted in the project "Opportunities and Barriers of Direct Manufacturing Technologies")

- **Process Integration:** Process integration refers to the integration of AM-processes into conventional manufacturing processes, and how to fit AM products into the manufacturing chain.

- **Economic (Process) Efficiency:** Frequently, the economic efficiency of AM-technologies was addressed. Firstly, low-budget AM-machines, and secondly process efficiency are mentioned as important fields of action. Mentioned aspects are the reduction of costs for removal of restraints, finishing of parts, as well as material costs, service costs etc.

Standardized design rules are mandatory to enable AM for DM.

- **Design Rules:** AM-compatible design is quoted as another major field of action. Particularly noteworthy is that the vast majority of the participants regard (standardized) design rules as a mandatory step to enable AM for DM.

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

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

Economic impact of “design optimization” needs to be estimated.

- **New finishing techniques:** These are regarded as an important action field by the majority of the respondents. The goal is to improve and accelerate AM-processes and to increase qualitative reproducibility of AM-parts that are directly “ready to use” and to reduce additional costs. For example, automated finishing techniques are named as necessary fields of research.
- **Quality Assurance:** For quality assurance there is also a great need for action from the participants’ point of view. The part quality of additively manufactured parts is still inferior to conventionally manufactured parts. Surface quality, same strength values in all 3 axes, dimensional accuracy, and microstructural analysis during and after the production are just some aspects. Long-term static and dynamic properties are also quoted as important. In-process online monitoring and quality control procedures as well as Non-Destructive Inspection (NDI) or a quality control with Six Sigma were addressed as well.
- **Software Solutions:** The link between CAD-models and analysis tools is regarded to be important. For instance, it would be a great benefit for generating internal structures directly. E.g. lattice structures could be calculated and adapted according to various requirements and tested under different conditions.
- **Standardization and Certification:** To increase the acceptance of AM, common standards have to be elaborated, special requirements of the various industries, e.g. fire resistance of materials/parts, have to be taken into account for certification, which in turn requires a common understanding along the value chain. Furthermore, certification for new materials is regarded as an important step towards DM.
- **Supply Base:** Supply Base seems to be highly ranked on the participants’ agenda. One central challenge is attributed to the limited quantity of existing service bureaus and to the quantity of raw material suppliers. Benchmarking of technology suppliers – different machines/brands and material suppliers – is indicated as a facilitating factor for increasing market transparency.
- **Education:** Education is especially frequently mentioned as an important aspect. To facilitate educational institutions to access AM-technologies, it is necessary to transfer knowledge in teaching and training qualification. Reciprocally, knowledge from research institutions has to be transferred into practice. Moreover, it is required to make both new and existing AM-users

Transfer of knowledge in teaching and training is crucial.

aware of AM's potential and to educate the staff. Especially designers need to be qualified for designing for AM.

- **Open Innovation:** Open Source for design, development and manufacturing as well as Cloud Production are named as fields of research that will significantly gain in importance for both, machine manufacturers and material suppliers. This may be an appropriate way for a collaborative development of new processes and material between technology suppliers and technology end-users. An "App Store" for software and designs may be a solution for exchanging process parameter apps and files.
- **Future Research and Interest:** To increase the penetration of AM, future research in the field of AM needs to be aligned with market and industry needs. Therefore, developments of existing and untapped business areas have to be anticipated in order to early develop ways to timely exploit these potentials. Quoted fields of interest are: concept model realization for macro testing of micro-electromechanical systems (MEMS), devices concepts (micro and mesoscale) etc. Further interests are: recyclability of AM-products, organ development, cell deposition and AM-technologies at the micro- and nanoscale.

Implications for Research Strategies

Now, the question is, how can these findings be leveraged for the development of research strategies in AM. We have already stated that it is necessary to align the technology development with current and future requirements applications of AM impose on DM. This directly implies that research projects with maximum benefits for potential AM-users need to be pursued. This requires consistent and demand-oriented research strategies.

Advancements required for the realization of the selected applications can be deduced directly by contrasting the applications, specifically the included technological and market requirements, and the technology's current performance. Technological requirements emerge directly from the applications; market requirements can be deduced from the market scenarios. The requirements then basically represent research fields that need to be investigated. To determine the research demand, additionally the current research activities and intensity – the state-of-the-art research landscape – need to be taken into account.

Technological requirements represent research fields that need to be explored.

As a result, the major technological requirements that need to be fulfilled in order to advance AM towards DM were revealed in the mentioned project. Moreover, the two expert surveys conducted within the AM-community have disclosed other points of interest. These requirements and points of interest were consolidated to deduce research fields that generally need to be investigated.

1.4 Summary

This chapter has outlined the development of Additive Manufacturing as an emerging technology with fascinating possibilities. Over the last decade, AM has been growing from Rapid Prototyping and an experimental stage to an industry-applicable technology.

A lot of industries are seeking for opportunities how to capitalize on the benefits AM provides, e.g. the “Freedom of Design”. New industries progressively draw their attention to AM’s potential. New business models and chances in supply chains have been emerging. As well, global research initiatives funded by different governments spark new impulses in the research landscape. Established and newly founded research centers, e.g. in the UK, the US or Germany are continuously striving to close gaps in the research landscape and to transfer the research results into tangible outcomes for the industry.

However to reach this, consistent and demand-oriented research strategies are needed. To ensure future relevance and success of research strategies, these need to be based on a visionary look into the future. A visionary sight into the future occurred in the previous project “Opportunities and Barriers of Direct Manufacturing Technologies”. Relevant branches and future applications for AM were identified and resulting requirements on significant future advancements of AM-technologies were derived.

The requirements give hints on aspects to be considered in future research strategies. For instance, technological implications can be deduced, such as the need for the development of design rules or increasing the process stability of AM-processes. In a next step, we need to take a look into the research landscape in order to reveal the need for research activity.

2

Additive Manufacturing Research Map

In the previous chapter, the development of AM has been sketched; therefore an overview on industrial efforts and governmental initiatives on advancing the technology as well as an overview on trends affecting AM and vice versa have been provided. In addition, the recently conducted project was briefly described. As a result, the major technological requirements need to be fulfilled in order to advance AM towards DM were revealed in the mentioned project. Moreover, the two expert surveys conducted within the AM-community have disclosed other points of interest. These requirements and points of interest were consolidated to deduce research fields that generally need to be investigated. The question is: Is there still any research demand within the identified research fields? This leads to other questions:

- Which research fields are represented in the research landscape?
- What are the current research initiatives in these research fields?
- Who is investigating in AM?
- How is the allocation of research fields to the research institutes?
- How high is the research intensity then?
- Are there any research fields that are highly relevant for industrial penetration of AM in the future but currently not in scope of AM-research in the landscape?

White spots in the research landscape can be deduced by current research activities with the future relevance of research fields.

To provide responses on these questions in order to determine the research demand in AM, the Heinz Nixdorf Institute and the DMRC conducted the two following surveys:

- Survey on Additive Manufacturing Research Map: the object is the determination of the research activity and the corresponding research intensity within the AM research landscape. The goal is an AM Research Map.
- Survey on the Future Relevance of AM: the main purpose was to get a sound overview on the future relevance of the determined research fields for the industry, and additionally to categorize the research fields into short-term-relevant (urgently required) and long-term-relevant (strategically required) research fields.

Merging the current research activities and intensity with the future relevance of the research fields (e.g. accessible market potential), for instance research fields that are of importance in the future and are barely developed at the same time – so called *white spots* can be revealed.

In the present chapter, an excerpt of these results is presented. Chapter 2.1 presents the characteristics of the research institutes that were taken into consideration for the development of the Research Map. Chapters 2.2 and 2.3 respectively yield an overview on the determined segmentation of the research landscape and AM-technologies that were addressed in the survey. The Research Map, including the key findings on research intensity and the evaluation of institute-specific and technology-specific research intensity is part of chapter 2.4. The results deduced from the survey on the Future Relevance of AM will be addressed in chapter 3.

Proceeding for the Development of the AM Research Map

First step is the creation of the AM Research Map.

Against the background of the key findings from the preceding project, the project "Research Strategies for AM" was initiated. The first step is the creation of the Additive Manufacturing Research Map. The Research Map should include information about:

- Research institutes,
- Research fields,
- AM-technologies and
- Research intensity.

18 research institutes were selected to be examined in the Research Map.

In the project, initially a group of 40 (major) institutes dealing with AM were identified. Firstly, information regarding these institutes was collected to get a sound overview of these institutes' research focus and range. Based on the collected information, the group of 40 institutes was reduced to 25 institutes to be considered in a more detailed examination. Exemplary selection criteria were the institutes' relative visibility and extent of research in AM. The selected 25 institutes were described in characteristics; the information was collected via desk research. Finally, 15 institutes were selected to be examined in the Research Map (see figure 2-1); the selection criteria were DMRC specific. These 15 finally selected institutes were concisely described in comprehensive profiles.

In a subsequent step, research fields for the segmentation of the AM research landscape were identified; impulses therefore were given by the requirements that were deduced within the strategic product planning conducted in the preceding project.

The research landscape was segmented into 43 research fields.

All in all, 43 research fields were identified; these were concretized and clustered to 6 categories:

- Material Research,
- Product Research,
- Process Research,
- Process Integration,
- Quality Control and
- Simulation.

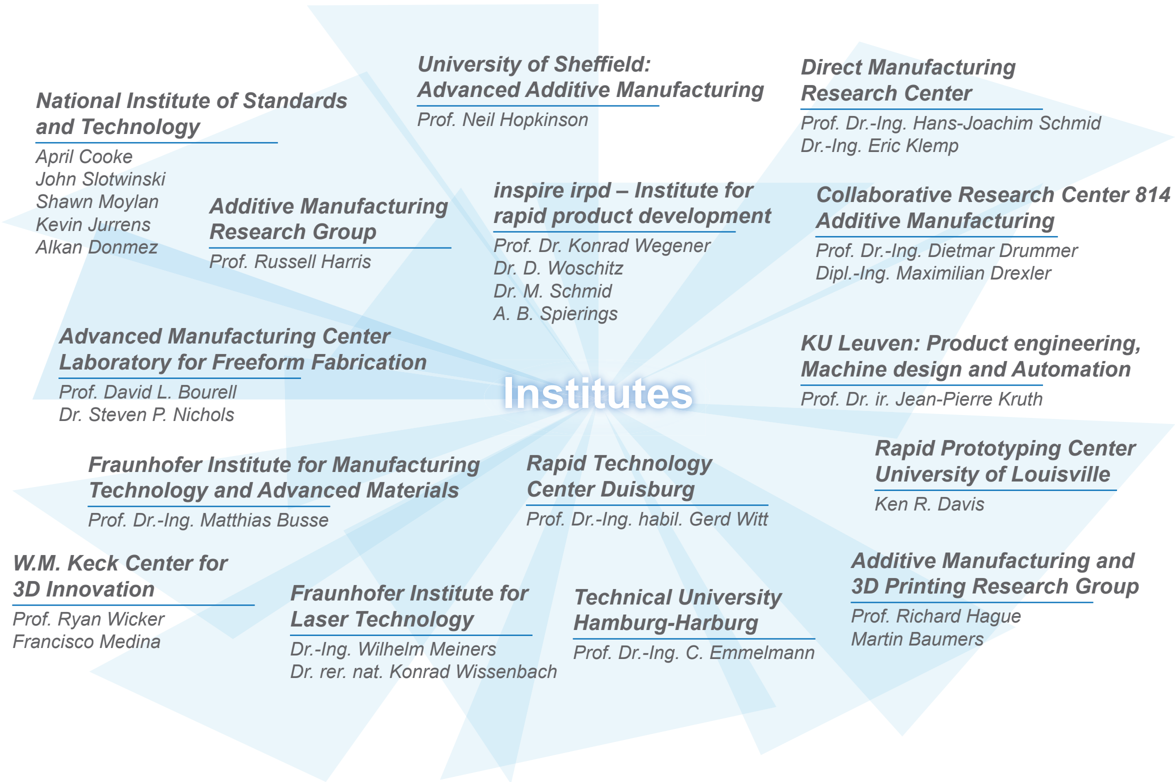


Figure 2-1: Overview of institutes considered in the survey on Additive Manufacturing Research Map

Four categories of AM-technologies were considered in the Research Map.

In addition, four categories of AM-technologies were selected to be considered in the analysis of the AM research landscape:

- Fused Layer Modeling Technologies,
- Powder Bed Fusion Plastic Technologies,
- Powder Bed Fusion Metal Technologies and
- Polymerization Technologies.

Research intensity for selected institutes was determined for each research-field-/technology-combination.

In a next step, as part of a survey the research intensity for the selected institutes was determined; therefore the institutes were assisted in telephone and personal interviews. Our thanks go to all institutes which contributed the information to create the AM Research Map.

The results were used to develop the Additive Manufacturing Research Map. Based on this, strengths/weaknesses profiles of the institutes were developed, differentiating research field specific and technology specific profiles. As part of a second survey the future relevance of the research fields was estimated. On this basis, arising *white spots* in the AM research landscape were deduced.

2.1 Research Institutes

Research institutes were characterized in profiles.

This chapter presents the selected institutes that were analyzed in detail as part of the survey on the Additive Manufacturing Research Map. For the characterization, comprehensive profiles were developed, including general information, focal points of research, and information on the institutes' stakeholders. General information encompasses statements on the institutes' vision, goals and the general category of research, comprising the options basic, applied or service oriented research. Financial, human and technical resources the institutes is equipped with is considered in the profile as well.

The focal point of research gives a clue about the applied technologies, the research fields and selected research projects the institute is dealing with. In addition a list of recent publications is provided in the profile. The section stakeholders yields an overview of the industrial focus, the respective industry and research partners/networks and the corresponding value propositions towards these stakeholders. In the following, the profiles of selected institutes are presented.

Additionally, the profiles include radar charts, indicating the institute's activity aggregated for the six defined categories from the Research Map: materials research, product research, process research, process integration, quality control and simulation. The diameter of the bubbles in these charts indicates how many research fields the respective institute addresses in its research work. A small diameter indicates that research is done in two research fields at maximum, the medium one specifies a research activity at most in nine research fields, and the large one points to a research activity in at least ten research fields. This data directly derives from the AM Research Map, and is briefly explained in chapter 2.4.

The data for the profiles was collected via desk research using the institutes' websites indicated in the contact field. Many institutes review and updated the information.

2.1.1 Advanced Manufacturing Center

Advanced Manufacturing Center (AMC) – Laboratory for Freeform Fabrication (LFF)

Short description of the institute

The Laboratory for Freeform Fabrication (LFF) was founded in 1988, following Carl Deckard's remarkable invention of Selective Laser Sintering (SLS), one of the first freeform fabrication processes. The LFF is part of the Advanced Manufacturing Center which was established in 2004 to initiate, support and coordinate research and education in advanced manufacturing and materials processing, to disseminate the research results to potential users and provide resources for education. LFF is active in research in diverse areas related to freeform fabrication.

Since 1990, lhe LFF has been hosting of the SFF Symposium.

Contact

Prof. David L. Bourell
Dr. Steven P. Nichols, Center Director
The University of Texas at Austin
Department of Mechanical Engineering
Cockrell School of Engineering University Station C2200
Austin, TX 78712, USA
Web: http://web.engr.utexas.edu/amc/

Categorization

Basic research | Applied research | Service

Resources

Not specified

Employees

46 employees (9 faculty and 20 graduate/postgraduate students with administrative and technical support staff)

Equipment (machines, measurement equipment etc.)

Not specified

Goals

The specific aims of the AMC/LLF include:

- Initiation, support and coordination of research and education in advanced manufacturing, design and materials processing
- Dissemination of the research results to potential users
- Promotion and provision of resources for education
- Researchers in the LFF represent considerable depth and breadth, including process development, materials, applications and modeling

Vision

The vision of the LFF is to increase the penetration of Solid Freeform Fabrication (SFF) processes besides the fabrication of small lot metal components economically by providing technologies for the fabrication of compositional heterogeneous, geometrically complex components that are extremely difficult or impossible to make by conventional methods.

Recent advancements from the UT Laboratory for Freeform Fabrication are leading to the next generation of SFF, especially focusing on functional prototyping and testing, new fabrication methods for optical components, instrumented structures and multiple-material parts.

Focal point of research

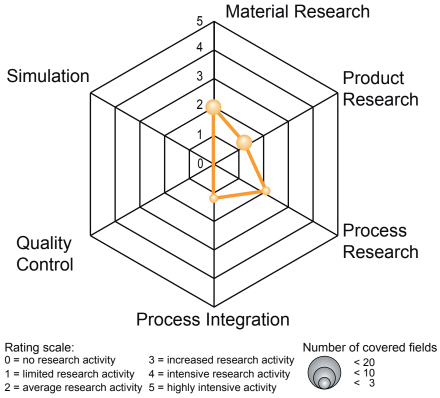
Applied technologies

- ■ Powder Bed Fusion (LS, SLM, LC, MS)
  - ☒ Plastic-based
  - ☒ Metal-based
  - ☐ Ceramic-based
- ☐ Polymer Vat (SL, µSL, DLP)
- ☐ Directed Energy/Metal Deposition (LENS, PMD, EBF³)
- ☐ Sheet Lamination (LLM, LOM, LMP)
- ☐ Material Extrusion (FLM, FDM, MJS)
- ☐ Binder Jetting (3D-Printing, M³D)
- ☐ Material Jetting (MJM, PJM)
- ☐ Hybrid (CMB, UC)
- ☐ _______________

Research fields

- ☐ Build-up rates
- ☐ Build chamber volume
- ☒ Manufacturing costs
- ☒ Material properties (e.g. mechanical, electrical, thermal)
- ☐ Process tolerances
- ☒ Part tolerances
- ☒ Design rules
- ☐ Combining processes
- ☐ Product optimization
- ☐ _______________

Research profile



Current research projects

- Multidisciplinary University Research Initiative: Materials and Manufacturing Science and Engineering of Direct Methanol Fuel Cells
- Collaborative Research: Innovations in Product Flexibility
- A Flexibility-Based Approach for Collaborative Design
- Teaching Automation and Control in Elementary Grades
- CAREER: Neuromotor Adaptations for Successful Transtibial Amputee Gait: Interactions with Limb Loading and Prosthetic Design Characteristics
- Dynamic Ankle-Foot Orthoses for Enhanced Function and Injury Prevention
- Negative stiffness structures for mechanical damping
- Thermal management in polyamide laser sintering
- Comparison of direct and indirect laser sintering of stainless steel
- Lower-limb prosthetic and orthotic design optimization
- Mechanically induced stochastic resonance to improve amputee gait
- 3D hierarchical nanomanufacturing for active photonics on a chip
- Advanced laser manufacturing of polymer nanocomposites
- Low-cost, direct-digital nanomanufacturing with simultaneous process monitoring

Publications

Recent publications

- Ventura, J.D.; Klute, G.K.; Neptune, R.R.: The effects of prosthetic ankle dorsiflexion and energy return on below-knee amputee leg loading. Clinical Biomechanics (in press), 2011
- Ventura, J.D.; Klute, G.K.; Neptune, R.R.: The effect of prosthetic ankle energy storage and return properties on muscle activity in below-knee amputee walking. Gait & Posture, 33(2), 2011, p. 220-226
- Bourell, D.L.; Beaman, J.J.: Electrochemical Deposition of Metal Ions in Porous Laser Sintered Inter-metallic and Ceramic Pre-forms, Proc. NSF CMMI Grantees Conference, Atlanta GA, 2011
- Chakravarthy, K.; Watt, T.J.; Bourell, D.L.: The use of high-speed video as an in-bore diagnostic for electromagnetic launchers. In: IEEE Transactions on Plasma Science, 39#2, 2011, p. 809-814
- …

Stakeholder

Overview stakeholder

Automotive industry	**Machine manufacturer**
Medical industry	Material supplier
Aerospace industry	**Government**
Electronics industry	**Research institutes**
Committees	**Students**

Industrial partners

- Boeing
- Texas High School Project
- National Instruments
- Cockrell School of Engineering
- Solid Concepts
- Limes Group

Value proposition

- High value expertise in advance manufacturing diverse companies can profit from

Research partners / Networks

- Office of Naval Research (ONR)
- National Science Foundation
- Stanford University
- South Texas VA Medical Center
- Andrew J. Gitter Research Center
- VA RR&D Center for Limb Loss Prevention & Prosthetic Engineering
- University of Delaware

Value proposition

- Education in advanced manufacturing, design, and materials processing
- Knowledge transfer

Services rendered

- Research includes industrial projects of varying size and duration. The Industrial Affiliates Program provides special opportunities for industry to interact with the Lab.

Figure 2-2: Detailed profile of the Advanced Manufacturing Center

2.1.2 Additive Manufacturing Research Group

Additive Manufacturing Research Group (AMRG)

Short description of the institute

The Additive Manufacturing Research Group (AMRG) at Loughborough University ranks among the worlds' leading centers for AM research, development and dissemination. Its fundamental and applied research focus on the development of AM-processes and materials, software and associated elements such as design. We have one of the world's most comprehensive additive manufacturing laboratories, supported by state-of-the-art testing and analysis facilities.

The AMRG is funded by the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing.

Loughborough University

Contact

Prof. Russell Harris
Additive Manufacturing Research Group
School of Mechanical and Manufacturing Engineering
Wolfson Building, Loughborough University
Loughborough LE11 3TU, United Kingdom
Web: www.lboro.ac.uk/research/amrg

Categorization

Basic research (selected) | **Applied research** (selected) | Service

Resources

Not specified

Employees

25 employees

Equipment (machines, measurement equipment etc.)

- EOS P390 and P100
- 3D Systems Viper SLA
- MTT SLM 100
- Stratasys Dimension SST 1200 and FDM 2000
- Z-Corp ZPrinter 450 and 510
- 3D Systems Thermojet
- Objet Connex500
- Ultrasonic Consolidation
- Roland LPX250 laser scanner
- Faro silver arm with non-contract 3D laser scanners head
- Desktop Engine 3D portable scanner

Goals

The specific aims of the AMRG include:

- Development and qualification of new and existing AM-technologies and materials
- Development of suitable design and software solutions
- Transfer of newly researched technologies into industrial application
- The enhancement and improvement of AM processes for specific industrial applications
- Knowledge dissemination through journal publications, books and conferences

Vision

The AMRG at Loughborough University conduct and service a broad scope of research activities ranging from highly fundamental investigations to translational activities. The majority of their research activities are conducted in collaboration with industrial partners and encompass a broad range of sectors including aerospace, automotive, consumer, sports, electronics and medical. Much of their work is cross-disciplinary and as such is conducted across different academic schools of the University and externally, both in the UK and internationally.

Focal point of research

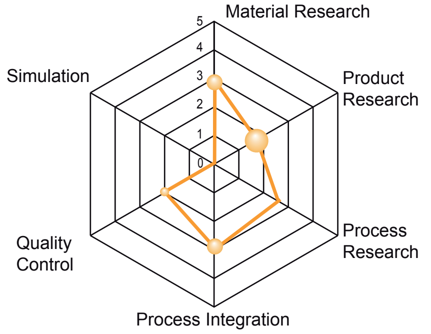
Applied technologies

- ■ Powder Bed Fusion (LS, SLM, LC, MS)
  - ☒ Plastic-based
  - ☒ Metal-based
  - ☐ Ceramic-based
- ☒ Polymer Vat (SL, µSL, DLP)
- ☐ Directed Energy/Metal Deposition (LENS, PMD, EBF³)
- ☐ Sheet Lamination (LLM, LOM, LMP)
- ☒ Material Extrusion (FLM, FDM, MJS)
- ☒ Binder Jetting (3D-Printing, M³D)
- ☒ Material Jetting (MJM, PJM)
- ☒ Hybrid (CMB, UC)
- ☐ ______________

Research fields

- ☐ Build-up rates
- ☐ Build chamber volume
- ☒ Manufacturing costs
- ☒ Material properties (e.g. mechanical, electrical, thermal)
- ☒ Process tolerances
- ☒ Part tolerances
- ☒ Design rules
- ☒ Combining processes
- ☒ Product optimization
- ☒ Software tools (CAD integration etc.)

Research profile



Rating scale:
0 = no research activity
1 = limited research activity
2 = average research activity
3 = increased research activity
4 = intensive research activity
5 = highly intensive research activity

Number of covered fields
< 20
< 10
< 3

Current research projects

- Artificial vascularised scaffolds for 3D-tissue regeneration
- Standardization in Additive Manufacturing
- Automated Biometric Design Integration
- Complex Surgery Simulation for Medical Training
- Smart Material Structures by Ultrasonic Consolidation
- Ultrasonic Consolidation for Manufacturing Aerospace Wing Structures
- Solid-state Additive Manufacture of Novel Multi-functional Metal Matrix by Ultrasonic Consolidation
- Fractionalization of surfaces for printing
- Jetting of Reactive Polymers
- Reinforcing additive manufacturing research cooperation between CMRDI and ERA
- Additive manufacturing of prostheses, orthoses and wearable medical devices
- Additive manufacturing of implants, surgical guides and surgical instruments

Publications

Recent publications

- Gatto, M.; Memoli, G.; Shaw, A.; Sadhoo, N.; Gelat, P.; Harris, R.A.: Three-Dimensional Printing (3DP) of neonatal head phantom for ultrasound: Thermocouple embedding and simulation of bone. In: Medical Engineering and Physics, 34(7), 2012, p. 929-937
- M.M. Savalani, M.M.; Hao, L.; Dickens, P.M.; Zhang, Y.; Tanner, K.E.; Harris, R.A.: The effects and interactions of fabrication parameters on the properties of selective laser sintered hydroxyapatite polyamide composite biomaterials. In: Rapid Prototyping Journal, 18(1), 2012, p.16-27
- Harris, R.A.; Savalani, M.M.; Hao, L.; Dickens, P.M.; Zhang, Y.; Tanner, K.E.: The effects and interactions of fabrication parameters on the properties of selective laser sintered hydroxyapatite polyamide composite biomaterials. In: Rapid Prototyping Journal, 18(1), 2012, p.16-27
- ...

Stakeholder

Overview stakeholder

Automotive industry	Machine manufacturer
Medical industry	Material supplier
Aerospace industry	Government
Electronics industry	Research institutes
Committees	Students
Other industries	

Industrial partners

- EOS
- Nottingham University Hospitals NHS
- University Hospitals Leicester NHS
- BMW
- Honda
- Constellium
- Solidica
- Fabrisonic

Value proposition

- Cutting-edge facilities and unique expertise/experience of academic team in working with industrial partners on collaborative research projects

Research partners / Networks

- University of Louisville
- Fraunhofer IPA
- Fraunhofer IPT
- Fraunhofer IWM
- Katholic University Leuven
- TNO
- Aalto University
- Albert-Ludwigs University of Freiburg
- National Physical Laboratory
- ASTM International Committee F42 on AM Technologies

Value proposition

- Knowledge transfer

Services rendered

- The AMRG also provides technology transfer and consultant services to industry.

Figure 2-3: Detailed profile of the Additive Manufacturing Research Group

2.1.3 Collaborative Research Center 814

Collaborative Research Center 814 - Additive Manufacturing

Short description of the institute

CRC 814 is a collaborative research center for additive manufacturing within the University of Erlangen-Nuremberg (FAU).

The CRC 814 is as an ideal complement to the EAM (Engineering of Advanced Materials). In the project area E of the EAM materials for light-weight construction are developed and investigated, but up to now without the possibility of additive manufacturing. The CRC closely cooperate with the Bavarian Laser Center (blz).

SFB 814
ADDITIVE FERTIGUNG

Contact

Prof. Dr.-Ing. Dietmar Drummer
Dipl.-Ing. Maximilian Drexler
Collaborative Research Center 814
Am Weichselgarten
91058 Erlangen
Germany
Web: http://www.sfb814.forschung.uni-erlangen.de

Categorization

Basic research (selected)	Applied research	Service

Goals

The Collaborative Research Center 814 focuses on the research areas:

- Powder materials
- Processes including simulation and components
- Beam and powder-based technologies
- Deeper understanding of the processes and a wider range of optimized plastic and metal materials for process and application
- Generate multi-material components (graded and hybrid parts)
- Enabling the processability of multi-functional composite materials and material combinations with new material properties and new constructive solutions based on reproducible, robust and measurable processes

Vision

The research of the CRC 814 focuses on fundamental scientific questions. Getting a better understanding of the behavior of powders during the process of production is the first aim of the CRC 814. This knowledge is very useful for developing new and optimized powder materials as well as optimizing machine construction and process settings, and to achieve optimum results, i.e. to gain a broad basis of fundamental inter-relations for optimized component properties.

Resources

About € 8.7 million for the years 2011 - 2015

Employees

different professors (chairs of the University)

38 scientific staff

Equipment (machines, measurement equipment etc.)

- ARCAM EBM-S12
- ARCAM EBM-A2
- EOSINT P 380 (via blz)
- DTM Sinterstation 2000 (via LKT)

Focal point of research

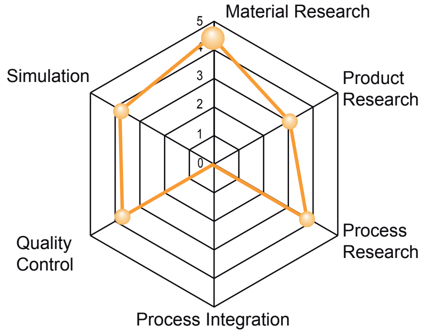
Applied technologies

- ■ Powder Bed Fusion (LS, SLM, LC, MS)
  - ☒ Plastic-based
  - ☒ Metal-based
  - ☐ Ceramic-based
- ☐ Polymer Vat (SL, µSL, DLP)
- ☐ Directed Energy/Metal Deposition (LENS, PMD, EBF³)
- ☐ Sheet Lamination (LLM, LOM, LMP)
- ☐ Material Extrusion (FLM, FDM, MJS)
- ☐ Binder Jetting (3D-Printing, M³D)
- ☐ Material Jetting (MJM, PJM)
- ☐ Hybrid (CMB, UC)
- ☐ ______________

Research fields

- ☒ Build-up rates
- ☐ Build chamber volume
- ☐ Manufacturing costs
- ☒ Material properties (e.g. mechanical, electrical, thermal)
- ☒ Process tolerances
- ☒ Part tolerances
- ☒ Design rules
- ☒ Combining processes
- ☒ Product optimization
- ☒ Software tools (CAD integration)

Research profile



Rating scale:
0 = no research activity
1 = limited research activity
2 = average research activity
3 = increased research activity
4 = intensive research activity
5 = highly intensive activity

Number of covered fields
< 20
< 10
< 3

Current research projects

Powder / materials
- Production and in-situ functionalization of polymer particles in the liquid phase
- Modification and functionalization of powders in the gas phase
- Characterization of polymer and powder characteristics
- Conditional aging process of plastics for film build-up method
- ...

Processes
- Simulation of the manufacturing process using geometrically complex particles
- Process strategies for the selective electron beam melting
- Process strategies for the selective laser melting of plastic powders
- ...

Components
- Optimization of the structure in the process of anisotropic materials
- Macroscopic modeling, simulation and optimization of selective beam melting with powder materials
- Incremental in-line testing for additive manufacturing

Publications

Recent publications
- Riedelbauer, D.; Mergheim, J.; McBride, A.; Steinmann, P.: Macroscopic Modelling of the Selective Melting Process. In: PAMM, Volume 12, Issue 1, 2012, p. 381-382
- Laumer, T.; Karg, M.; Schmidt, M.: Laser Beam Melting of Multi-Material Components. In: Physics Procedia 39, 2012, p. 518-525
- Drummer, D.; Wudy, K.; Kühnlein, F.; Drexler, M.: Polymer Blends for Selective Laser Sintering: Material and Process Requirements. In: Physics Procedia 39, 2012, p. 509-517
- Drummer, D.; Drexler, M.; Kühnlein, F.: Influence of powder coating on part density as a function of coating parameters. In: I. Drstvensek (Ed.), iCAT 2012 - 4th International Conference on Additive Technologies, DAAAM International, Vienna, Maribor, 2012
- Drummer, D.; Kühnlein, F.; Drexler, M.: Fundamental Investigations of the Degradation Behavior of PA12 - Plastic Powders. In: Drstvensek, I. (Ed.), iCAT 2012 - 4th International Conference on Additive Technologies, DAAAM International, Vienna, Maribor, 2012.

Stakeholder

Overview stakeholder
- Automotive industry
- Machine manufacturer
- Medical industry
- Material supplier
- Aerospace industry
- Government
- Electronics industry
- Research institutes
- Committees
- Students
- Other industries

Industrial partners
- Not yet released

Value proposition
- Economical production of technically innovative products with a high variance in terms of quantity and design

Research partners / Networks
- Not yet released

Value proposition
- Regular exchange of experience
- Basic research; generation of fundamentally new knowledge in materials, processes and components

Services rendered
- Basic research

Figure 2-4: Detailed profile of the Collaborative Research Center 814

2.1.4 Direct Manufacturing Research Center

Direct Manufacturing Research Center (DMRC)

Short description of the institute

The Direct Manufacturing Research Center DMRC is a research center of the University of Paderborn and constitutes a proactive collaboration of key technology stakeholders who have a common interest in advancing Rapid Prototyping technology into dependable, production rugged Direct Manufacturing technology.

For its research work, the Direct Manufacturing Research Center was awarded as "Ort des Fortschritts" (engl. place of technological progress) by the Ministry of Innovation, Science and Research of the State of North Rhine Westphalia in 25th November 2011.

DMRC
DIRECT MANUFACTURING RESEARCH CENTER

Contact

Prof. Dr.-Ing. Hans-Joachim Schmid
Dr. Ing. Eric Klemp
University of Paderborn
Direct Manufacturing Research Center
Mersinweg 3
33098 Paderborn, Germany
Web: www.dmrc.uni-paderborn.de/en

Categorization

Basic research	**Applied research**	Service

Resources

Revenues 2009/2010: €535.608

Earnings 2009/2010: €651.666

Forecast: €11 million until 2016

Employees

2 directors (commercial and scientific)

8 professoers (chairs of University of Paderborn)

18 staff (technical and scientific)

Equipment (machines, measurement equipment etc.)

- Stratasys Fortus 400 mc
- EOS Eosint P 395
- SLM Solutions 250 HL
- Universal testing system Instron 5569
- Universal testing system Zwick HB 250
- Instrument for thermal photography P 640, FLIR
- Scanning Electron Microscope (SEM), Phenom SEM, Phenom World
- Optical 3D-multi-sensor-system kolibri MULTI, Fraunhofer
- Surface roughness measurement, Hommel Etamic T8000, Jenoptic
- Blasting, Junior®, Normfinish
- Centrifugal force device, ECO 18, Otec
- Moisture measuring device, AQUATRAC E3, Brabernder
- Scanning Electron Microscope etc.

Goals

The specific aims of the DMRC include:

- Advancing vital technological progress for broader application of DM in series production
- Incubation and transfer of promising technologies to companies
- Promote the corresponding paradigm change from production driven design to function driven design
- Training and education of the next generation of engineers
- Performing independent market studies and benchmarks
- Becoming an internationally renowned platform for exchange of best practices as well as optimal procedures
- Perform application oriented as well as fundamental research projects along the complete value chain
- Define process, product and quality standards

Vision

The DMRC strives for advancing Additive Manufacturing technologies from Rapid Prototyping to dependable Direct Manufacturing technologies. To achieve this, the DMRC focus on the continuous and interdisciplinary development of Direct Manufacturing technologies involving respective experts depending on specific topics, and informs potential users about the advantages of the technologies. The DMRC envisions the creation of a world class community through present best practice, tools and techniques and establishes a platform for benchmarking of tools and techniques.

Focal point of research

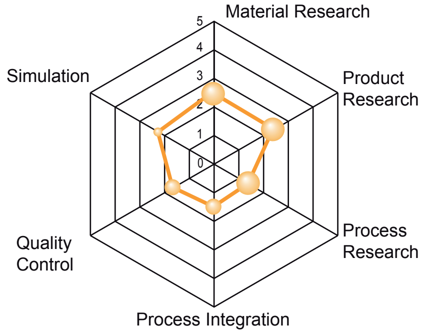
Applied technologies

- ■ Powder Bed Fusion (LS, SLM, LC, MS)
  - ☒ Plastic-based
  - ☒ Metal-based
  - ☐ Ceramic-based
- ☐ Polymer Vat (SL, µSL, DLP)
- ☐ Directed Energy/Metal Deposition (LENS, PMD, EBF³)
- ☐ Sheet Lamination (LLM, LOM, LMP)
- ■ Material Extrusion (FLM, FDM, MJS)
- ☐ Binder Jetting (3D-Printing, M³D)
- ☐ Material Jetting (MJM, PJM)
- ☐ Hybrid (CMB, UC)
- ☐ ______________

Research fields

- ☒ Build-up rates
- ☐ Build chamber volume
- ☒ Manufacturing costs
- ☒ Material properties (e.g. mechanical, electrical, thermal)
- ☒ Process tolerances
- ☒ Part tolerances
- ☒ Design rules
- ☐ Combining processes
- ☒ Product optimization
- ☐ ______________

Research profile



Rating scale:
0 = no research activity
1 = limited research activity
2 = average research activity
3 = increased research activity
4 = intensive research activity
5 = highly intensive activity

Number of covered fields
< 20
< 10
< 3

Current research projects

- Direct Manufacturing Design Rules (2.0)
- Costing analysis for Additive Manufacturing during product lifecycle
- Research strategies for Addititive Manufacturing
- Fatigue strength properties of SLM-components
- FDM part quality manufactured with ULTEM*9085
- Fused Deposition Modeling: Improvement of the FDM process quality; surface treatment methods
- Influencing factors on DM part quality by polymer Laser Sintering
- Opportunities and barriers of direct manufacturing technologies
Optimization of lattice structures manufactured by Selective Laser Melting; Light weight construction
- Product optimization for SLM-process; Innovative SLM-materials
- QM-system for DM-processes at the DMRC
- Quantification of surface quality obtained by post processing of Laser Sintered parts: Determination of Material Properties by references to a real product optimized for Laser Sintering
- Fatigue Life Manipulation
- Prevention against product piracy – protect innovations (Cutting-Edge Cluster it's OWL)
- Future RepAIR and Maintenance for Aerospace industry (EU-project)

Publications

Recent publications

- Leuders, S.; Thöne, M.; Riemer, A. ; Niendorf, T.; Tröster, T.; Richard, H.A.; Maier, H.J.: On the mechanical behaviour of titanium alloy TiAl6V4 manufactured by selective laser melting: Fatigue resistance and crack growth performance, Int. Journal of Fatigue, 2012
- Zimmer, D.; Adam, G.: Design Rules for Additive Manufacturing. In: Konstruktion 7/8-2013
- Bagsik, A.; Schöppner, V.; Klemp, E.: Extensive Analysis of the Mechanical Strength Properties of Fused Deposition Modeling Parts manufactured with Ultem9085. 5th Int. PMI Conference, Ghent/Belgien, 12th-14th September, 2012
- Rüsenberg, S.; Weiffen, R.; Knoop, F.; Gessler, M.; Pfisterer, H.; Schmid, H.-J.: Controlling the Quality of Laser Sintered Parts Along the Process Chain. Int. SFF Symposium, Austin, 2012
- Gausemeier, J.; Echterhoff, N.; Wall. M.: Thinking ahead the Future of Additive Manufacturing – Innovation Raodmapping of Required Advancements. Heinz Nixdorf Institute, Paderborn, 2013
- Lindemann, C.; Jahnke, U.; Moi, M.; Koch, R.: Analyzing Product Lifecycle Costs for a Better Understanding of Cost Drivers in Additive Manufacturing, Solid Freeform Fabrication Symposium, 2012

Stakeholder

Overview stakeholder

Automotive industry	Machine manufacturer
Medical industry	Material supplier
Aerospace industry	Government
Electronics industry	Research institutes
Committees	Students
Toy industry	Other

Industrial partners

- Blue Production GmbH
- Eisenhuth GmbH & Co. KG
- EOS – Electro Optical Solutions GmbH
- Evonik Industries AG
- LEGO Systems A/S
- Stükerjürgen Aerospace Composites GmbH & Co. KG
- Siemens AG
- SLM Solutions GmbH
- Stratasys, Inc.
- The Boeing Company Corp.

Value proposition

- Cooperation with key experts
- Access to all the results created by DMRC research
- Pooling with other companies and benefit from additional public funding
- Providing solutions for specific problems
- Co-steer direction of DM research strategy
- Publishing

Research partners / Networks

- University of Paderborn:
    - Product Engineering
    - Design and Drive Technology
    - Materials Science
    - Polymer Engineering
    - Computer Application and Integration in Design and Planning
    - Mechanical and Environmental Process Engineering
    - Applied Mechanics
    - Automotive Lightweight Construction
- Standardization committees (VDI, ASTM)
- AMRC, TPRC, IVHM

Value proposition

- Knowledge transfer and dissemination
- Training and education of the next generation of engineers
- Performing independent market studies/ benchmarks on methods and processes
- Lectures/Module on AM

Services rendered

- Prototyping
- Generic projects are basic research tasks with partners of the DMRC (e.g. FDM, LS, SLM)
- Specific projects deal with a particular technical task
- Studies
- External projects
- Chair of Aerospace Session at the RapidTech

Figure 2-5: Detailed profile of theDirect Manufacturing Research Center

2.1.5 Fraunhofer Institute for Manufacturing Technology and Advanced Materials

Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM)

Short description of the institute

The Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM) in Bremen focuses on practice-oriented research in Adhesive Bonding Technology and Surfaces and Shaping and Functional Materials. Founded in 1949, the IFAM develops products and processes to the stage of application. Rapid Product Development is one of the diverse research fields (biomaterial technology, electrical systems etc.) of IFAM.

The institute is strongly cross-linked within the Fraunhofer Additive Manufacturing Alliance.

Fraunhofer IFAM

Contact

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Wiener Strasse 12
28359 Bremen, Germany
Web: www.ifam.fraunhofer.de

Categorization

Basic research | **Applied research** | Service

Resources

General budget 2011: € 40 million

Employees

More than 500 employees

Equipment (machines, measurement equipment etc.)

- DMLS EOS M270/EOS M 250X
- 3D-Printer Z-Corp SPECTRUM Z 510
- 3D-Printing ProMetal RX1
- OPTOMEC M3D
- 3D-Scanner smart optics ACTIVITY 91

Goals

The IFAM focuses on three research areas:

Casting technology and light metal technology; micro- and nanostructuring; powder technology and sintering technology.

Research and Development:

- Powder- and material development for RP-systems
- Process development for metals and ceramics
- Process development for follow-up procedure steps

Technology-transfer:

- Industrial technology transfer
- Demonstration and support by the application of RP-technologies
- Support for system integration

Vision

In order to form smart products, components are tailored with functional properties. Technologies and process chains for the production, modification and processing of powders into complex parts are developed.

The IFAM focuses the cost-effective integration of function into parts and structures. The vision is to be a reliable partner for industrial companies for the development of customer and application oriented materials and processes.

Focal point of research

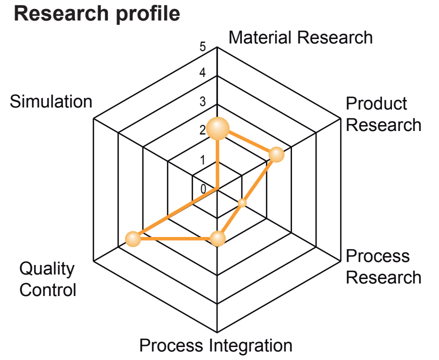
Applied technologies

- ■ Powder Bed Fusion (LS, SLM, LC, MS)
  - ☐ Plastic-based
  - ☒ Metal-based
  - ☐ Ceramic-based
- ☐ Polymer Vat (SL, µSL, DLP)
- ☐ Directed Energy/Metal Deposition (LENS, PMD, EBF³)
- ☐ Sheet Lamination (LLM, LOM, LMP)
- ☒ Material Extrusion (FLM, FDM, MJS)
- ☒ Binder Jetting (3D-Printing, M³D)
- ☐ Material Jetting (MJM, PJM)
- ☐ Hybrid (CMB, UC)
- ☐ _______________

Research fields

- ☐ Build-up rates
- ☐ Build chamber volume
- ☒ Manufacturing costs
- ☒ Material properties (e.g. mechanical, electrical, thermal)
- ☒ Process tolerances
- ☒ Part tolerances
- ☒ Design rules
- ☒ Combining processes
- ☒ Product optimization
- ☒ Software tools (CAD integration etc.)

Research profile



Rating scale:
0 = no research activity
1 = limited research activity
2 = average research activity
3 = increased research activity
4 = intensive research activity
5 = highly intensive activity

Number of covered fields
< 20
< 10
< 3

Current research projects

- European funded project CompoLight, 7th framework programme - GA no. 213477: The project deals with Rapid Manufacturing of lightweight metal components, namely the ability to produce complex internal geometries of the following types: geometrically defined singular structures (e.g. cooling channels), geometrically defined repetitive structures (e.g. lightweight parts) and geometrically undefined structures (e.g. porous parts).
- Continuous mass production for customized products funded by Volkswagen-Stiftung

Publications

Recent publications

- Aumund-Kopp, C.; Petzoldt, F.; Uckelmann, I.: Rapid Manufacturing – Am Markt umgesetzte Verfahren Pulvermetallurgie in Wissenschaft und Praxis. Bd. 24, 2008, p. 181-196
- Aumund-Kopp, C.; Busse, M.; Isaza, J.; Petzoldt, F.: Medical Instruments Produced by Selective Laser Melting –Chances and Possibilities. In: Proceedings of DDMC 2012, Berlin, 14 - 15 March, 2012
- Marquardt, A.; Recknagel, C.; Langer, I.; Müller, S.; Kieback, B.: Improved mechanical properties of low alloyed sintered steels through Fe-Mn-Si master alloys. European Congress and Exhibition on Powder Metallurgy, Barcelona, 2011
- Bertol, L.S.; Junior, W.K.; Silva, F.P.D.; Aumund-Kopp, C.: Medical design: Direct metal laser sintering of Ti-6Al-4V. Materials and design 31, No. 8, 2010, p. 3982-3988

Stakeholder

Overview stakeholder

Automotive industry	Machine manufacturer
Medical industry	Material supplier
Aerospace industry	Government
Electronics industry	Research institutes
Committees	Students
Other industries	

Industrial partners

- Wide range of national and international companies of different industry sectors

Value proposition

- Availability of interdisciplinary material, process and data handling competence, comprising modeling, product- and process simulation, as well as realization of prototypes going to product development
- Enhancing the competitiveness, especially of small and medium-size companies, by improving the time to market of their products

Research partners / Networks

- Wide range of national and international research institutions of different research sectors
- Rapid Manufacturing platform

Value proposition

- Knowledge transfer

Services rendered

- Simulation: Multi-Phase-Topology-Optimization
- Development of process from the generation of 3D data models to additive processes and part finishing and control
- Material development and process optimization
- Support for the integration of AM-technologies: Consulting, feasibility studies and technology transfer
- Prototyping for medical industry and mechanical engineering industry, manufacturing of mold inserts

Figure 2-6: Detailed profile of the Fraunhofer Institute for Manufacturing Technology and Advanced Materials

2.1.6 Fraunhofer Institute for Laser Technology

Fraunhofer Institute for Laser Technology (ILT)

Short description of the institute

The Fraunhofer Institute for Laser Technology ILT is one of the world's leading contract research and development institutes in the field of laser development and laser application. The core competencies include the development of new laser beam sources and components, laser manufacturing technologies and rapid manufacturing.

The institute won the North Rhine-Westphalia's 2011 Innovation Award for Additive Manufacturing.

Fraunhofer ILT

Contact

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Germany
Web: www.ilt.fraunhofer.de

Categorization

Basic research	**Applied research**	Service

Resources

Not specified

Employees

330 Employees

Equipment (machines, measurement equipment etc.)

Various Selective Laser Melting plants for rapid manufacturing

Goals

- Improvement of part quality and build-up rates
- Expansion of their range of materials, such as Ni-based super-alloys and ceramic materials
- Expansion of the producible structure sizes, particularly through using new laser beam sources
- Qualification of the SLM process for customized application and mass production
- Development of systems and components
- Manufacturing components with individual geometries (e.g. hollow structures)
- SLM-component concept
- Integration of SLM into existing manufacturing process
- Training in research and education
- Strengthening the technical and scientific capabilities of German companies
- Play an active role in the formulation and organization of research policy goals

Vision

The aim of the ILT is to be at the international top position in transferring technology to industrial application. In order to reach this aim the institute strategically expand its knowledge across the network and consequently focus on customer requirements.

Focal point of research

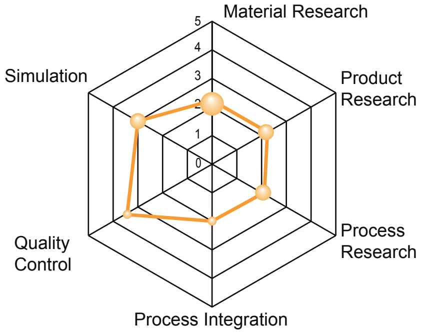
Applied technologies

- ■ Powder Bed Fusion (LS, SLM, LC, MS)
  - ☒ Plastic-based
  - ☒ Metal-based
  - ☒ Ceramic-based
- ☐ Polymer Vat (SL, µSL, DLP)
- ☒ Directed Energy/Metal Deposition (LENS, PMD, EBF³)
- ☐ Sheet Lamination (LLM, LOM, LMP)
- ☐ Material Extrusion (FLM, FDM, MJS)
- ☐ Binder Jetting (3D-Printing, M³D)
- ☐ Material Jetting (MJM, PJM)
- ☐ Hybrid (CMB, UC)
- ☐ ______________

Research fields

- ☒ Build-up rates
- ☒ Build chamber volume
- ☒ Manufacturing costs
- ☒ Material properties (e.g. mechanical, electrical, thermal)
- ☒ Process tolerances
- ☒ Part tolerances
- ☒ Design rules
- ☒ Combining processes
- ☒ Product optimization
- ☒ Simulation / Thermo analysis

Research profile



Rating scale:
0 = no research activity
1 = limited research activity
2 = average research activity
3 = increased research activity
4 = intensive research activity
5 = highly intensive activity

Number of covered fields
< 20
< 10
< 3

Current research projects

More than 20 research projects in national and international consortiums with strong industry background, addressing the main topics:

- In-line quality assurance for additive mass production
- Additive manufacturing of high-strength aluminum components
- Additive manufacturing in satellite technology
- Additive manufacturing of copper components
- Additive manufacturing of components made of high-strength ceramics with selective laser melting
- Additive Manufacturing of individual patient implants on the basis of computer tomography data
- Bioresorbable implants using Selective Laser Melting
- Laser cladding and integrated process chain for blade tip repairs
- Laser material deposition of internal contours
- Laser material deposition with variable track widths
- Process monitoring of laser metal deposition
- Process diagrams for high-deposition-rate laser metal deposition
- Surface digitization as a means of geometry data acquisition for the laser cladding processes

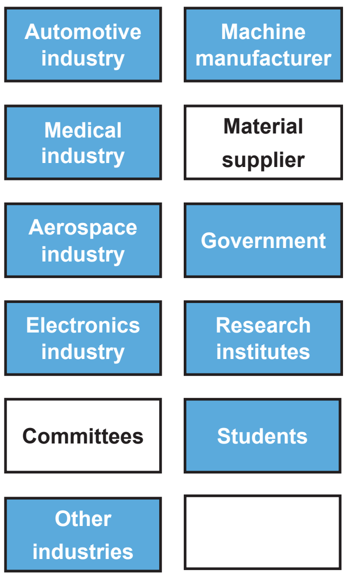
Publications

Recent publications

- Bremen, S.; Buchbinder, D.; Meiners, W.; Wissenbach, K.: Selective Laser Melting – A Manufacturing Method for Series Production? Proceedings of DDMC 15th & 16th March, Berlin, 2012
- Dongdong G.; Hagedorn, Y.-C.; Meiners, W.; Meng, G.; Santos Batista, R. J.; Wissenbach, K.; Poprawe, R.: Densification behavior, microstructure evolution, and wear performance of selective laser melting processed commercially pure titanium. Acta Materialia, Kidlington, Elsevier Science, 2012, p. 3849-3860
- Brandl, E.; Heckenberger, U.; Holzinger, V.; Buchbinder, D.: Additive manufactured AlSi10Mg samples using Selective Laser Melting (SLM): Microstructure, high cycle fatigue, and fracture behavior. Materials & Design Vol. 34 , 2012, p. 159-169
- Buchbinder, D.; Schleifenbaum, H.; Heidrich, S.; Meiners, W.; Böltmann, J.: High Power Selective Laser Melting (HP SLM) of Aluminium Parts. Physics Proceedia Vol. 12, No. Part 1, 2011, p. 271-278
- ...

Stakeholder

Overview stakeholder



Industrial partners

Partners are all OEMs for SLM Equipment, optical components, software solutions and renown companies of the automotive, aerospace and medical industry.

Value proposition

- Tailoring solutions and their cost-effective implementation into costumer requirements, in order to enhance their competitiveness
- Support industry's needs for new specialists and managerial staff through project-based partnerships with customers

Research partners / Networks

- RWTH Aachen: Chair for Laser Technology LLT, Chair for the Technology of Optical Systems TOS, and Chair of Non-linear Dynamics of Laser-Processing NLD
- European Laser Institute ELI
- Photonics 21Photonics 21
- University of Central Florida
- University of Michigan

Value proposition

- Supporting a vertical structure in research and development, enhancing new perspectives and applications for the benefit of society
- Modern infrastructure, excellent industrial contacts, method competencies in project management, team and entrepreneur spirit, international coworkers, short communication ways as well as foreign stays in the USA and France

Services rendered

- Collaborative Research Training Programs
- Feasibility studies
- Numerical simulations
- Plasma diagnostics

Figure 2-7: Detailed profile of the Fraunhofer Institute for Laser Technology

2.1.7 Additive Manufacturing and 3D Printing Research Group

Additive Manufacturing and 3D Printing Research Group

Short description of the institute

The Additive Manufacturing and 3D Printing Research Group at the University of Nottingham includes internationally leading academics and one of the world's most comprehensive additive manufacturing laboratories. It is supported by state-of-art testing facilities.

Additionally, the group hosts the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing. The Additive Manufacturing and 3D Printing Research Group is the annual host of the International Conference on Additive Manufacturing and 3D Printing.

Contact

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Martin Baumers
Additive Manufacturing and 3D Printing Research Group
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Nottingham NG7 2RD, United Kingdom
Web: www.nottingham.ac.uk/engineering-rg/manufacturing/3dprg/index.aspx

Categorization

Basic research | Applied research | Service

Employees

19 employees

Budget

£10 Million

Equipment (machines, measurement equipment etc.)

Not specified

Goals

The specific aims of the Additive Manufacturing and 3D Printing Research Group include:

- Pushing forward the development and application of next-generation, multi-material and multifunctional Additive Manufacturing and 3D Printing technologies with a focus on end-use focused 3D structures and components
- Fostering industrial cooperation to ensure the leading position of the United Kingdom in the Additive Manufacturing business
- To guarantee this status, especially the beneficial industrial application of AM products is made a constant subject of research.

Vision

The Additive Manufacturing and 3D Printing Research Group operates in both fundamental and applied research focused on Additive Manufacturing and 3D Printing with a focus on process and materials development, software and business management. It also focuses on the investigation of new processes and design systems. The major aim is to concentrate on enabling greater potential value and application by integrating additional engineering or systems functionality within a single component. Furthermore another aim is to exploit the unrivalled design freedoms associated with 3D Printing to enable next-generation products demanded by key industries.

Focal point of research

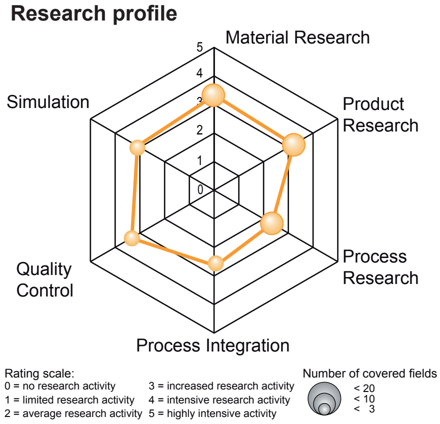
Applied technologies

- ■ Powder Bed Fusion (LS, SLM, LC, MS)
  - ☐ Plastic-based
  - ☐ Metal-based
  - ☐ Ceramic-based
- ☐ Polymer Vat (SL, µSL, DLP)
- ☐ Directed Energy/Metal Deposition (LENS, PMD, EBF³)
- ☐ Sheet Lamination (LLM, LOM, LMP)
- ☐ Material Extrusion (FLM, FDM, MJS)
- ☐ Binder Jetting (3D-Printing, M³D)
- ☐ Material Jetting (MJM, PJM)
- ☐ Hybrid (CMB, UC)
- ☐ _______________

Research fields

- ☐ Build-up rates
- ☐ Build chamber volume
- ☐ Manufacturing costs
- ☐ Material properties (e.g. mechanical, electrical, thermal)
- ☐ Process tolerances
- ☐ Part tolerances
- ☐ Design rules
- ☐ Combining processes
- ☐ Product optimization
- ☐ _______________

Research profile



Current research projects

- Multifunctional Additive Manufacturing design (Development of design systems and rules)
- Jetting of reactive polymers for mechanical and biological applications (With exceptional focus on biodegradable and other functional materials)
- Area sintering for multifunctional Additive Manufacturing (Striving for increased speed, resolution and repeatability)
- Jetting of electronic tracks (Focus on dielectric and conductive elements)
- Development of modeling techniques for the jetting of multifunctional devices
- Nano-functionalized optical sensors (Two-Photon polymerization)

Publications

Recent publications

- Baumers, M.; Tuck, C.; Hague, R.: Realised levels of geometric complexity in additive manufacturing. In: International Journal of Product Development, Volume 13, Issue 3, May 2011, Pages 222-244
- Goodridge, R.D.; Tuck, C.J.; Hague, R.J.M.: Laser sintering of polyamides and other polymers Progress in Materials Science. 57(2), 229-267, 2012
- Goodridge, R.D.; Shofner, M.L.; Hague, R.J.M.; McClelland, M.; Schlea, M.R.; Johnson, R.B; Tuck, C.J.: Processing of a polyamide-12/carbon nanofibre composite by laser sintering Polymer Testing. 30(1), 94-100, 2011
- Baumers, M.; Tuck, C.; Bourell, D.L.; Sreenivasan, R.; Hague, R.: Sustainability of additive manufacturing: Measuring the energy consumption of the laser sintering process. In: Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Volume 225, Issue 12, December 2011, Pages 2228-2239
- etc.

Stakeholder

Overview stakeholder

Automotive industry	Machine manufacturer
Medical industry	Material supplier
Aerospace industry	Government
Electronics industry	Research institutes
Committees	Students
Other industries	

Industrial partners

Not specified

Value proposition

- Providing AM solutions in close industrial cooperation
- Enhancing the applicability of AM parts
- Consulting services

Research partners / Networks

- ESPRC
- TSB
- AM system vendors
- Technology users
- Additive Manufacturing Research Group at Loughborough University

Value proposition

- Lectures

Services rendered

- Consulting services
- Annual host of the International Conference on Additive Manufacturing and 3D Printing

Figure 2-8: Detailed profile of the Additive Manufacturing and 3D Printing Research Group

2.1.8 Institute for Rapid Product Development

inspire irpd – Institute for rapid product development

Short description of the institute

The institute for rapid product development (irpd) deals with methods and technologies that shorten the time-to-market intervals of products. The main focus is the further development of LS- and SLM-processes and machines including corresponding materials and the transfer of the possibilities into applications. The institute offers also reverse engineering, consulting and services across all industries, such as in the device, machine, tool and die making, medicine, architecture, automotive industry.

inspire irpd institute for rapid product development

Contact

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inspire AG irpd
Lerchenfeldstrasse 5
9014 St. Gallen
Switzerland
Web: www.inspire.ethz.ch/irpd

Categorization

Basic research | Applied research | Service

Resources

The facilities of the irpd now has a replacement value of 5 million francs.

Employees

18 employees

Equipment (machines, measurement equipment etc.)

- EOS P 760, 2 further SLS machines
- Concept Laser M1 and M2
- 2 R&D SLS machines
- 3D-Printing (3DP)
- 3D-Scanner (GOM, Minolta)
- DSC, TGA for plastic materials
- Powder analyse equipment (particle size & -shape distribution, flowability, fluidisation)
- Optical and tactile surface quality
- Microscopy, SEM, EDX
- Polishing/edging of samples
- Mechanical test equipment (static, dynamic)
- Impact toughness (Charpy)
- MFI (Melt flow index)
- Access to further equipment at Empa and ETH

Goals

The specific aims of the irpd include:

- In cooperation with inspire ZH, projects focusing on quality optimization of AM-components and process reliability are defined
- Development of new AM-materials for LS and SLM processes
- Further development of AM-technologies
- Increase penetration in various industries including teaching at ETH and universities of applied sciences
- Deduction of required research and development activities based on the experience gained in industrial projects
- Manufacturing of AM-parts of high and reproducible quality with added value at reasonable costs

Vision

The institute strives for the establishment of a model factory for Additive Manufacturing for demonstrating the functionality and capabilities of AM-technologies. In addition, the institutes committed itself to spread AM within various industries, showing up the opportunities for economical production of geometrically complex, additive manufactured structures, minimizing the risk of product development by planning, market research or early application of these technologies for ergonomic and functional analysis. These activities are complemented with specific research focussing on processes, materials and applications with added value.

Focal point of research

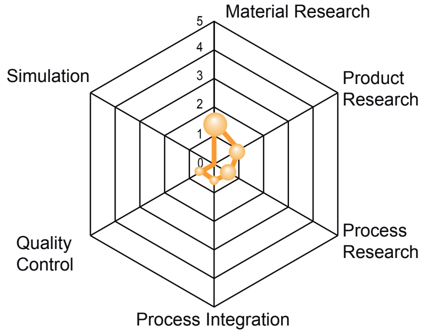
Applied technologies

■ Powder Bed Fusion (LS, SLM, LC, MS)
  ☒ Plastic-based
  ☒ Metal-based
  ☐ Ceramic-based
☐ Polymer Vat (SL, µSL, DLP)
☐ Directed Energy/Metal Deposition (LENS, PMD, EBF³)
☐ Sheet Lamination (LLM, LOM, LMP)
☐ Material Extrusion (FLM, FDM, MJS)
☐ Binder Jetting (3D-Printing, M³D)
☐ Material Jetting (MJM, PJM)
☐ Hybrid (CMB, UC)
☐ ______________

Research fields

☒ Build-up rates
☐ Build chamber volume
☒ Manufacturing costs
☒ Material properties (e.g. mechanical, electrical, thermal)
☒ Process tolerances
☒ Part tolerances
☒ Design rules
☒ Combining processes
☒ Product optimization
☐ ______________

Research profile



Rating scale:
0 = no research activity
1 = limited research activity
2 = average research activity
3 = increased research activity
4 = intensive research activity
5 = highly intensive activity

Number of covered fields
< 20
< 10
< 3

Current research projects

Commission for Technology and Innovation (CTI) Projects (nationally funded)

Some projects are:

- Industrial production of turbine applications with SLM
- Innovative climate system for automotive application

EU Projects

- 7th Framework Program of the EU: inspire is active in 4 projects, two of them are already finished (StepUp, DirectSpare)
- irpd is active member in the SASAM project, aiming for drawing a roadmap for future standardisation in additive manufacturing
- irpd is initiator and member in the OXIGEN project, aiming the development of new high temperature materials for turbine applications

Direct contract research

- Bilateral R&D projects with industrial partners, focusing material, process and production issues, optimization of engineering/ reverse engineering of geometries for these processes to enable increased functional integration; the projects are generally confidential; results are not being published

Publications

Recent publications

- Schmid, M.: iCoPP – Polypropylen für Additive Manufacturing, in SWISS ENGINEERING STZ - PLASTICS.NOW!, Koemedia AG, St.Gallen, 2012
- Schmid, M.; Levy, G.: Quality Management and Estimation of Quality Costs for Additive Manufacturing with SLS. In: Proceedings of Direct Digital Manufacturing Fraunhofer Conference (DDMC). Berlin, Germany, March 14-15, 2012
- Schmid, M., Levy, G.; Wegener, K.: Flowability of Powders for Selective Laser Sintering (SLS) investigated by Round Robin Test. In: proceedings of International Conference on Advanced Research in Virtual and Rapid Prototyping (VRAP 2013) Leira, Portugal, 1st - 5th October 2013, CRC Press, Taylor & Francis, London, 2013
- Spierings, A.: Selective Laser Melting im Fokus. In: Swiss Engineering STZ, 2013, p. 42-43.
- Spierings, A.: Standardisierung in additiver Fertigung erhält Schub. In: Technische Rundschau, volume 3, p. 46-47, 2012
- ...

Stakeholder

Overview stakeholder

Automotive industry	Machine manufacturer
Medical industry	Material supplier
Aerospace industry	Government
Electronics industry	Research institutes
Committees	Students
Other industries	

Industrial partners

- Starrag
- DGS Druckguss Systeme AG
- Valspar
- BMW
- MBN, Italy
- Siemens
- Alstom
- SwissMem

Value proposition

- Optimizing the quality of business processes to shorten time-to-market intervals of new products and improving the internal logistics processes

Research partners / Networks

- Empa, ETH Zurich
- Paul Scherrer Institute
- Fachhochschule St.Gallen
- Interstaatliche Hochschule für Technik Buchs
- University of Louisville, USA
- Loughborough University, GB
- Heriot Watt University, Scottland
- TNO, NL
- RM platform
- ASTM
- VDI
- ...

Services rendered

- Consulting e.g. for new process technologies and materials
- irpd provides support in the area of engineering, particularly reverse engineering (RE)
- Manufacturing of parts in small series in diverse plastic and metallic materials

Figure 2-9: Detailed profile of the Institute for Rapid Product Development

2.1.9 The Technical University of Hamburg-Harburg

Technical University Hamburg-Harburg (iLAS/LZN)

Short description of the institute

At the Technical University Hamburg-Harburg (TUHH) training of young engineers, as well as industry-related research is well established. Therefore, the Institute of Laser and System Technologies (iLAS) was founded in 2001 to obtain core competencies in innovative laser production technologies. In 2009, the LZN Laser Center North GmbH was founded as an application-oriented competence center which operates as a link between research and industry. Both institutes, LZN and iLAS, are in close cooperation.

Contact

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LZN Laser Zentrum Nord GmbH
Am Schleusengraben 14, 21029 Hamburg
Web: www.tu-harburg.de/ilas, http://www.lzn-hamburg.de

Categorization

Basic research | Applied research | Service

Goals

As the link between basic research and application, LZN and iLAS set innovative impulses for companies to improve their competitiveness and thereby strengthen their position on the market. The development of innovative optical and photonic production technologies and products through both Institutes will support companies in order to guarantee sustainable value creation with innovative optical technologies.

Competencies:

- AirLAS (Innovative lightweight construction and technology)
- MedLAS (Laser based manufacturing of medical devices)
- RoLAS (Robot supported laser processing of metal sheets)
- SynLAS (Automatic laser material processing of synthetic materials and fiber composites)
- ToolLAS (Innovative machine and tool manufacturing)
- ShipLAS (Efficient construction of 3D ship parts)

Vision

Their aim is to essentially improve, facilitate and accelerate knowledge and technology transfer from basic research to industrial applications. The research and development activities cover the entire production process to the finished product. The activities – supplemented by the aspects of education and training – in particular focus on laser technologies.

Resources

€21 million seed capital for the LZN

Estimated turnover (annually) €2.5 million

Employees

27 employees

Equipment (machines, Equipment (machines, measurement equipment etc.)

- Concept Laser M2 cusing
- EOS EOSINT M270xt
- EOS EOSINT P390
- SLM Solutions SLM 250HL
- High Power Test Rig (1 kW)
- Trumpf Deposition Line

For further information please follow this link:

http://www.lzn-hamburg.de/ueber-uns/infrastruktur.html#c929

Focal point of research

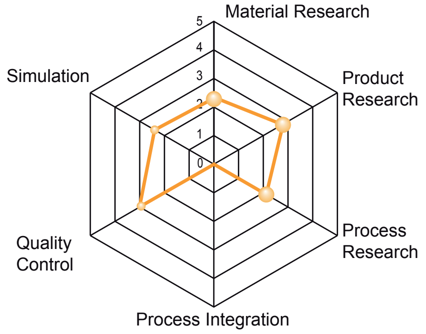
Applied technologies

- ■ Powder Bed Fusion (LS, SLM, LC, MS)
  - ☒ Plastic-based
  - ☒ Metal-based
  - ☐ Ceramic-based
- ☐ Polymer Vat (SL, μSL, DLP)
- ☒ Directed Energy/Metal Deposition (LENS, PMD, EBF³)
- ☐ Sheet Lamination (LLM, LOM, LMP)
- ☐ Material Extrusion (FLM, FDM, MJS)
- ☐ Binder Jetting (3D-Printing, M³D)
- ☐ Material Jetting (MJM, PJM)
- ☐ Hybrid (CMB, UC)
- ☐ ______________

Research fields

- ☐ Build-up rates
- ☐ Build chamber volume
- ☐ Manufacturing costs
- ☒ Material properties (e.g. mechanical, electrical, thermal)
- ☒ Process tolerances
- ☒ Part tolerances
- ☐ Design rules
- ☒ Combining processes
- ☒ Product optimization
- ☒ New Manufacturing technologies

Research profile



Rating scale:
0 = no research activity
1 = limited research activity
2 = average research activity
3 = increased research activity
4 = intensive research activity
5 = highly intensive activity

Number of covered fields
< 20
< 10
< 3

Current research projects

- TiLight: Innovative lightweight structures by bionic design and additive manufacturing in Ti-6Al-4V for aircraft applications
- AlaTin: Analysis of influence of powder material, part and process design, heat treatment and part finishing on mechanical properties of Ti-6Al-4V components
- KombiLAS: Aluminium prototypes and small series through hybrid manufacturing
- MegaFIT: Development of sensor concepts and process control for laser beam melting

Publications

Recent publications

- Emmelmann, C.: Bionic products by additive laser manufacturing. In: 'Manufacturing Innovations in Laser Additive Manufacture' workshop. Advanced Manufacturing Precinct – RMIT University, Melbourne (Australia) 27.-28.06.2012
- Emmelmann, C.: Additive Manufacturing von Funktionsbauteilen – Gegenwärtige Herausforderung auf dem Weg zur Serienproduktion. Lecture. „Additive Fertigung“ - Bauteil- und Prozessauslegung für die wirtschaftliche Fertigung des Münchner Kolloquiums. Augsburg 19.06.2012
- Seyda, V.; Kaufmann, N.; Emmelmann, C.: Investigation of aging processes of Ti-6Al-4V powder material in laser melting. Physics Procedia 39, 2012, pp. 425-431
- Klahn, C.; Bechmann, F.; Hofmann, S.; Dinkel, M.; Emmelmann, C.: Laser Additive Manufacturing of Gas Permeable Structures. Physics Procedia 41 iii-viii, 2013, pp. 866-872
- Wycisk, E.; Kranz, J.; Emmelmann, C.: Fatigue Strength of Light Weight Structures produced by Laser Additive Manufacturing in TiAl6V4. 1st International Conference of the International Journal of Structural Integrity, Porto (Portugal) 15.-28.06.2012

Stakeholder

Overview stakeholder

Automotive industry	Machine manufacturer
Medical industry	Material supplier
Aerospace industry	Government
Electronics industry	Research institutes
Committees	Students
Ship building Industry	Other Industries

Industrial partners

- Hofmann Werkzeugbau GmbH
- Hauni
- Airbus Operations Ltd.
- Blohm + Voss Shipyards Ltd.
- BMW AG
- Carl Cloos
- CONCEPT Laser Ltd.
- Daimler AG
- DMG Gildemeister GmbH
- E.C.H. Will GmbH
- EOS GmbH
- EWAG GmbH
- SLM-Solutions GmbH
- ...

Value proposition

- Empowering of industrial partners to become successful pioneers in the field of photonic/laser production.

Research partners / Networks

- Technical University of Hamburg-Harburg
- The Free and Hanseatic City of Hamburg
- TuTech Innovation GmbH
- Deutscher Verband für Schweißen und verwandte Verfahren e. V. (DVS)
- HansePhotonik e. V.
- tibb e. V.
- WLT - Wissenschaftliche Gesellschaft für Lasertechnik e.V
- Rapid Manufacturing Plattform
- Nortec
- DIN-Committee – Additive Manufacturing
- NorLiN – Northern Lightweight Design Network

Value proposition

- Knowledge dissemination
- Education

Services rendered

- Development: manufacture pilot series; check time, quality and costs
- Consulting: feasibility studies and consultancy services
- Education: technicians and engineers; knowledge transfer
- Research: application-oriented industrial research topics; public, state-run, federal and EU funded projects
- Prototyping and manufacturing of special parts in small numbers
- Covering the whole process chain from conception/construction to the finished part

Figure 2-10: Detailed profile of the Technical University Hamburg-Harburg

2.1.10 KU Leuven

KU Leuven: Product engineering, Machine design and Automation (PMA)

Short description of the institute

The Production Engineering, Machine Design and Automation (PMA) division is part of the Mechanical Engineering department in the Engineering Faculty of the KU Leuven in Belgium., The PMA has more than 20 years of experience in Additive Manufacturing. The range of its research activities is widespread. In the past they focused on SLA, at the moment their main research fields are in SLS/SLM. It has been involved in R&D activities that led to several major technological developments, patents and to the success of companies active in AM. The institute has patented a SLA liquid curtain recoating system.

Contact

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Catholic University of Leuven
Department of Mechanical Engineering, Division PMA
Celestijnenlaan 300B
B-3001 Leuven, Belgium
Web: www.kuleuven.be/english

Categorization

Basic research | Applied research | Service

Resources

Not specified

Employees

150 employees

Goals

- The PMA pursues a balance between long-term research, that is pivotal in order to sustain an advanced scientific level as well as short-term and application oriented research.
- In bilateral industrial projects, tailored solutions are assessed with regard to their industrial application
- It also provides general assistance and consulting.

Vision

The PMA focuses on non-conventional manufacturing processes. It strives to enhance established Additive Manufacturing technologies and to develop new methods for sheet metal forming (laser bending, single point incremental forming). The strong exploratory urge in the field of Additive Manufacturing already gave rise to the birth of well-known companies like Materialise, Metris (Nikon Metrology) and Layerwise.

Equipment (machines, measurement equipment etc.)

- SLS machines Selective Laser Melting machine (LM-Q), built by the research group equipped with a monitoring system
- DTM Sinterstation 2000
- Concept Laser M3
- Concept Laser M1 (Medical) equipped with a monitoring system
- EOSint M250
- Dimension 1200 (Stratasys)
- 2 X-ray CT-scanners:
- Nikon Metrology/Metris/Xtek 450 kV
- Nikon Metrology/Metris/Xtek 225kV-Metrology

Focal point of research

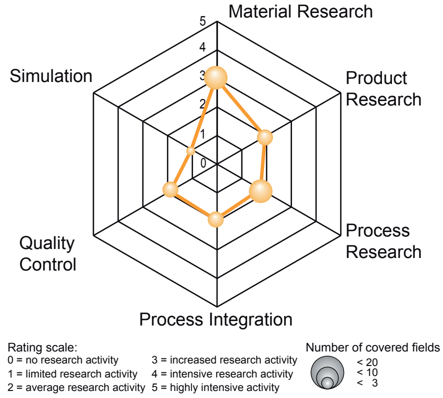
Applied technologies

■ Powder Bed Fusion (LS, SLM, LC, MS)
  ☒ Plastic-based
  ☒ Metal-based
  ☒ Ceramic-based
☐ Polymer Vat (SL, µSL, DLP)
☐ Directed Energy/Metal Deposition (LENS, PMD, EBF³)
☐ Sheet Lamination (LLM, LOM, LMP)
☐ Material Extrusion (FLM, FDM, MJS)
☐ Binder Jetting (3D-Printing, M³D)
☐ Material Jetting (MJM, PJM)
☐ Hybrid (CMB, UC)
☒ Laser Re-melting

Research fields

☒ Build-up rates
☐ Build chamber volume
☐ Manufacturing costs
☒ Material properties (e.g. mechanical, electrical, thermal)
☒ Process tolerances
☒ Part tolerances
☐ Design rules
☐ Combining processes
☒ Product optimization
☒ Software tools (CAD integration etc.)

Research profile



Current research projects

- Sheet Metal Oriented Prototyping and Rapid Manufacturing
- Materials and materials processes
- Selective Laser Sintering
- Analysis and exploitation of the interaction between materials and processes for a better machine ability of metallic materials and cermet in thermo-physical manufacturing
- 3D Laser scanning analysis of wear of amalgam substitutes in dentistry
- Rapid Prototyping and Manufacturing of Space Components
- Broadening the field of ceramic components by joint and interactive research on EDM machining technology, noval ceramic materials based on nano-powders made by SHS and design methodology
- Advanced control of Selective Laser Sintering and Selective Laser Melting techniques based on camera images
- Direct Rapid Manufacturing of Metallic and Ceramic (customized) Parts of industrial and Medical applications
- Effective Structural Health Monitoring with Additive Manufacturing
- Fundamental investigations into high-precision computed tomography of multi-material objects in view of dimensional quality control of assembled products or products with internal features.
- ...

Publications

Recent publications

- Deckers, J.; Shahzad, K.; Vleugels, J.;Kruth J.-P.: Isostatic pressing assisted indirect selective laser sintering of alumina components. In: Rapid Prototyping Journal, Volume: 18, Issue: 5, 2012
- Craeghs, T.; Clijsters, S.; Yasa, E.;Bechmann, F.; Berumen, S.; Kruth, J.-P.: Determination of geometrical factors in Layerwise Laser Melting using optical process monitoring. In: Optics and Lasers in Engineering, 49, 2011
- Yasa, E.; Deckers, J.; Kruth, J.-P.: The investigation of the influence of laser re-melting on density, surface quality and microstructure of selective laser melting parts. In: Rapid Prototyping Journal Volume: 17, Issue: 5, 2011
- Kruth, J.-P.; Badrossamay, M.; Yasa, E.; Deckers, J.; Thijs, L.; Van Humbeeck, J.: Part and material properties in selective laser melting of metals. 16th International Symposium on Electromachining (ISEM XVI), 2010

Stakeholder

Overview stakeholder

Automotive industry	**Machine manufacturer**
Medical industry	Material supplier
Aerospace industry	**Government**
Electronics industry	**Research institutes**
Committees	**Students**
Other industries	

Industrial partners

- Materialise
- Ford Motor Company
- WTCM
- GMP Poliuretani
- APR Aquacutting
- KUKA GmbH
- Charmilles Technologies Ltd.
- …

Value proposition

- Provision of consulting and assistance for industrial implementation of AM-technologies
- Increase added value together with clients

Research partners / Networks

- Involvement in Belgian (BELASNET) and European Laser Research Network (EULASNET)
- Vakgroep Mechanische Constructie en Productie Ugent
- Department MTM KU Leuven

Value proposition

- Knowledge transfer

Services rendered

- Consulting / Assistance
- Feasibility studies

Figure 2-11: Detailed profile of KU Leuven

2.1.11 National Institute of Standards and Technology

National Institute of Standards and Technology (NIST)

Short description of the institute

The National Institute of Standards and Technology (NIST) is a federal technology agency working with industry on the development and application of technologies, measurements and standards.

NIST is a non-regulatory agency of the United States Department of Commerce, consisting of six laboratories including: Engineering Laboratory, Information Technology Laboratory, Material Measurement Laboratory, Physical Measurement Laboratory, Center for Nanoscale Science and Technology and NIST Center for Neutron Research.

Contact

April Cooke; John Slotwinski; Shawn Moylan; Kevin Jurrens; Alkan Donmez
National Institute of Standards and Technology
100 Bureau Drive
Gaithersburg, MD 20878, USA
Web: www.nist.gov

Categorization

Basic research	Applied research	Service

Resources

NIST annual budget: US$ 819 million (2009)
US$ 856 million (2010)
US$ 750 million (2011)

Budget attributed to additive manufacturing: Not specified

Employees

2,900 scientists, engineers, technicians and support and administrative personnel

1,800 guest researchers and engineers from American companies and foreign nations

In the field of AM: 6

Equipment (machines, measurement equipment etc.)

- Direct Metal Laser Sintering
- 3D Printing
- Coordinate Measuring Machines
- Surface Profilometers
- High-Speed Videography (Visible and Infrared Spectrums)
- Ultrasonic Sensors

Goals

- The National Institute of Standards and Technology has the official mission to "Promote U.S. innovation and industrial competitiveness by advancing measurement science, standards and technology in ways that enhance economic security and improve our quality of life."
- Regarding additive manufacturing technologies, the Engineering Laboratory pursues the following goals:
- Development of standard test methods for additive metal processes enabling the industry to evaluate and improve the performance of additive manufacturing systems
- Development and delivery of enhanced measurement techniques supporting new, standardized methods for quantifying the material properties of the powders and the resulting manufacturing products

Vision

NIST will be the world's leader in creating critical measurement solutions and promoting equitable standards. NIST efforts stimulate innovation, foster industrial competitiveness, and improve the quality of life.

NIST is developing test methods that will provide essential elements of standards needed for additive manufacturing equipment, processes and materials. Better scientific understanding of material and process characteristics will point the way to improvements in additive manufacturing processes and products.

Focal point of research

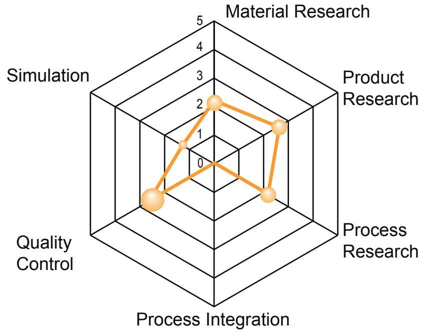
Applied technologies

- ■ Powder Bed Fusion (LS, SLM, LC, MS)
  - ☐ Plastic-based
  - ☒ Metal-based
  - ☐ Ceramic-based
- ☐ Polymer Vat (SL, μSL, DLP)
- ☐ Directed Energy/Metal Deposition (LENS, PMD, EBF³)
- ☐ Sheet Lamination (LLM, LOM, LMP)
- ☐ Material Extrusion (FLM, FDM, MJS)
- ☒ Binder Jetting (3D-Printing, M³D)
- ☐ Material Jetting (MJM, PJM)
- ☐ Hybrid (CMB, UC)
- ☐ ______________

Research fields

- ☐ Build-up rates
- ☐ Build chamber volume
- ☐ Manufacturing costs
- ☒ Material properties (e.g. mechanical, electrical, thermal)
- ☒ Process tolerances
- ☒ Part tolerances
- ☒ Design rules
- ☐ Combining processes
- ☐ Product optimization
- ☐ ______________

Research profile



Rating scale:
0 = no research activity
1 = limited research activity
2 = average research activity
3 = increased research activity
4 = intensive research activity
5 = highly intensive activity

Number of covered fields
< 20
< 10
< 3

Current research projects

- Materials standards for Additive Manufacturing
- Smart manufacturing processes and equipment program
- Develop measurement science for quantitative validation of additive manufacturing
- Development of composite structure digital manufacturing models
- Develop and deliver enhanced measurement techniques that support new, standardized methods for quantifying the material properties of both the powders used for additive manufacturing and resulting manufactured products

Publications

Recent publications

- Cooke, A.; Slotwinski, J.: Properties of Metal Powders for Additive Manufacturing: A Review of the State of the Art of Metal Powder Property Testing. NISTIR (under review), 2012.
- Moylan, S.; Cooke, A.; Jurens, K.; Slotwinski, J.; Donmez, M.A.: A Review of Test Artifacts for Additive Manufacturing. NISTIR 7858, 2012
- Slotwinski, J.; Cooke, A.; Moylan, S.: Mechanical Properties Testing for Metal Parts Made via Additive Manufacturing: A Review of the State of the Art of Mechanical Property Testing. NISTIR 7847, 2012
- Cooke, A.; Moylan, S.: Process Intermittent Measurement for Powder-Bed Based Additive Manufacturing. 2011
- Cooke, A.; Soons, J.: Variability in the Geometric Accuracy of Additively Manufactured Test Parts. 2010

Stakeholder

Overview stakeholder

Automotive industry	Machine manufacturer
Medical industry	Material supplier
Aerospace industry	Government
Electronics industry	Research institutes
Committees	Students
Other industries	

Industrial partners

- GE
- Boeing
- Rolls Royce
- Morris Technologies
- etc.

Value proposition

- Providing manufacturing and distribution consulting services which improve productivity
- Promoto industrial competitiveness

Research partners / Networks

- Carnegie Mellon University
- Lawrence Livermore National Lab
- Oak Ridge National Lab
- Air Force Research Lab
- Additive Manufacturing Consortium (AMC)
- EWI
- ASTM

Value proposition

- Promote U.S. innovation by advancing measurement science, standards and technology
- Enhance economic security and improve quality of life

Services rendered

Figure 2-12: Detailed profile of the National Institute of Standards and Technology

2.1.12 Rapid Prototyping Center

Rapid Prototyping Center, University of Louisville (RPC)

Short description of the institute

The Rapid Prototyping Center (RPC) belongs to the Department of Industrial Engineering of the University of Louisville and has been funded for a Direct Digital Manufacturing Center by the Navy to investigate and publish mechanical properties of polymers and metals for selected AM-processes. The University of Louisville has been assisting 70+ members of its industrial consortium with design, engineering and product development initiatives within its RPC since 1993, when it became the first US university to buy and operate Laser Sintering equipment. The RPC is now one of the most advanced prototyping facilities in the Louisville area. Prof. Stucker is chairman of the ASTM International Committee F42 on AM and was awarded with the Robert J. Painter Memorial Award for his service to standardization efforts in 2010.

UNIVERSITY OF LOUISVILLE

Contact

Ken R. Davis
J. B. Speed School of Engineering
University of Louisville
Louisville, Kentucky 40292
USA
Web: www.louisville.edu/speed/rpc

Categorization

Basic research | Applied research | Service

Resources

$1.35 million, Jul 2010 - Sep 2012 for Direct Digital Manufacturing

Employees

Director of Vogt Engineering Center
Manager, Rapid Prototyping Center Operations
Coordinator of Engineering Technical Services
Laser Development Engineer
Administrative Assistant, Vogt Engineering Center
Rapid Prototyping Center Co-operative Student

Equipment (machines, measurement equipment etc.)

- EOSINT M270
- Sinterstation 2500+ and 2000
- SLA-250
- FDM 8000
- Testing and microscopy machines

Goals

The specific aims of the RPC or the Department include:

- Education of enable graduates for successful professional practice of industrial engineering
- Providing problem-solving technology to industrial partners

Vision

The Department of Industrial Engineering has been dedicating itself to provide outstanding industrial engineering educational opportunities for regional, national and international students, while maintaining the societal commitment to the development of new knowledge through the integration of research, scholarship and practice.

The RPC commits itself to provide Prototyping Services to shorten time-to-market, save money and reduce costly delays in product development processes. Customers gain access to problem-solving technology as well as continuing research.

Focal point of research

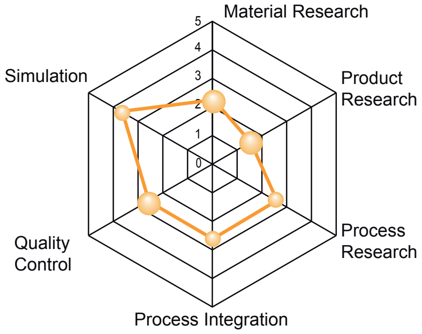
Applied technologies

- ■ Powder Bed Fusion (LS, SLM, LC, MS)
  - ☒ Plastic-based
  - ☒ Metal-based
  - ☐ Ceramic-based
- ☒ Polymer Vat (SL, µSL, DLP)
- ☒ Directed Energy/Metal Deposition (LENS, PMD, EBF³)
- ☐ Sheet Lamination (LLM, LOM, LMP)
- ☒ Material Extrusion (FLM, FDM, MJS)
- ☐ Binder Jetting (3D-Printing, M³D)
- ☐ Material Jetting (MJM, PJM)
- ☒ Hybrid (CMB, UC)
- ☐ ______________

Research fields

- ☐ Build-up rates
- ☐ Build chamber volume
- ☐ Manufacturing costs
- ☒ Material properties (e.g. mechanical, electrical, thermal)
- ☒ Process tolerances
- ☒ Part tolerances
- ☐ Design rules
- ☐ Combining processes
- ☒ Product optimization
- ☒ Recycling Process Control

Research profile



Rating scale:
0 = no research activity
1 = limited research activity
2 = average research activity
3 = increased research activity
4 = intensive research activity
5 = highly intensive activity

Number of covered fields
< 20
< 10
< 3

Current research projects

- Direct Digital Manufacturing Phase II, Office of Naval Research, PI- Starr, Co-PI: Usher, Gornet, Stucker. $1.35 million, Jul 2010 - Sep 2012
- Further Development and Transition into NAVAIR of a Novel, Integrated Ultrasonic Consolidation, Fused Deposition Modeling and Direct Write System, Brent Stucker, Office of Naval Research, $100,000, 2010 (recommended for funding starting March 2010; still in contracting as of Jan. 2010
- Implant Fabrication using Laser Engineered Net Shaping, Stucker, MedicineLodge, $188,441, 2007-2014
- Investigation of the Use of Laser Engineered Net Shaping (LENS) for Biomedical Implants, Stucker, MedicineLodge, $377,975, 2003-2012
- High Temperature Materials
- Process Characterization
- Material Quality and Recycling Process Control
- Direct Digital Manufacturing

Publications

Recent publications

- Starr, T.; Gornet, T.; Usher, J.: The Effect of Process Conditions on Mechanical Properties of Laser Sintered Nylon, (RPJ-03-2010-0027.R1) to appear Rapid Prototyping Journal, 2010
- Obielodan, J.O.; Janaki Ram, G.D.; Stucker, B.: Minimizing Defects between Adjacent Foils in Ultrasonically Consolidate Parts. In: Journal of Engineering Materials and Technology, 132(1), 2010
- Obielodan, J.O.; Ceylan, A.; Murr, L.E.; Stucker, B.: Multi-Material bonding in Ultrasonic Consolidation. In: Rapid Prototyping Journal, 16(3): 2010
- Yang, Y.; Janaki Ram, G.D.; Stucker, B.: An Analytical Energy Model for Metal Foil Deposition in Ultrasonic Consolidation. In: Rapid Prototyping Journal, 16(1): 20-28. 2010
- Gibson, I.; Rosen, D. W.; Stucker, B.: Additive Manufacturing Technologies – Rapid Prototyping to Direct Digital Manufacturing. Springer Verlag, New York, Heidelberg, Dordrecht, London, 2010

Stakeholder

Overview stakeholder

Automotive industry	Machine manufacturer
Medical industry	Material supplier
Aerospace industry	Government
Electronics industry	Research institutes
Committees	Students

Industrial partners

- Advantage Plastics & Engineering
- Brinly-Hardy Company
- Chromatography Research Supplies
- Climate Technologies - Emerson
- CMI - MPH/MPD
- Delta T - Big Ass Fans
- GE Company/GE Corp, R&D
- Grindmaster Crathco Systems, Inc.
- Hitachi Automotive Products (USA)
- Hi-Tech Mold & Tool, Inc.
- Paramount Industries
- The Boeing Company
- Zoeller Pump Company
- …

Value proposition

- Providing problem-solving technology to industrial partners

Research partners / Networks

- Georgia Institute of Technology
- Office of Naval Research
- Loughborough University
- National Science Foundation (NSF)
- National Institute of Health
- US Navy
- The Office of Naval Research

Value proposition

- Basic research and knowledge transfer

Services rendered

- Conceptual Modeling, Medical Modeling and Investment Casting using Stereolithography
- Conceptual Modeling, Functional Prototyping and Investment Casting using Selective Laser Sintering

Figure 2-13: Detailed profile of the Rapid Prototyping Center

2.1.13 Rapid Technology Center

Rapid Technology Center Duisburg (RTC)

Short description of the institute

The main focus of research activities of the Rapid Technology Center (RTC) at the University of Duisburg - Essen are recent problems concerning the development from Rapid Prototyping (RP) to Rapid Manufacturing (RM). Prof. Gerd Witt is chairman of the Committee on Rapid Prototyping at the VDI and is a selected reviewer at the AiF (Arbeitsgemeinschaft industrieller Forschungsvereinigungen).

Contact

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Rapid Technology Center
Institute for Product Engineering, Faculty of Engineering
University Duisburg-Essen
Lotharstr. 1
47057 Duisburg, Germany
Web: www.unidue.de/fertigungstechnik

Categorization

- Basic research
- Applied research
- Service

Resources

Not specified

Employees

14 employees

Equipment (machines, measurement equipment etc.)

- EOSINT M 270
- Formiga P 100
- DTM Sinterstation 2500 and 2000
- DTM Sinterstation 2500 HS
- Thermo Jet (two)
- Dimension SST1200es
- Infratec Thermal imaging system
- Coordinate measurement equipment: Nikon, Faro

Goals

The specific aims of the RTC include:

- Asset optimization and process monitoring
- Basic understanding of processes
- Qualification of new materials
- RM-based design
- Integration of specific functions into products

Vision

The vision of the RTC is based on the development of new materials, deeper knowledge of processes, RM-based design, development of medical equipment and the development of new application-fields for tool-less manufacturing processes.

Focal point of research

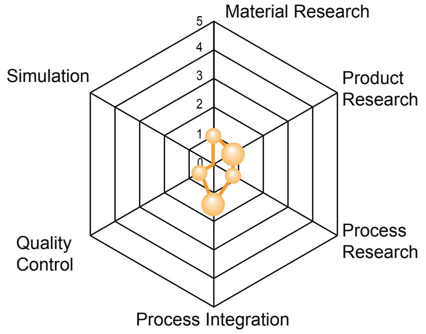
Applied technologies

- ■ Powder Bed Fusion (LS, SLM, LC, MS)
  - ☒ Plastic-based
  - ☒ Metal-based
  - ☐ Ceramic-based
- ☐ Polymer Vat (SL, μSL, DLP)
- ☐ Directed Energy/Metal Deposition (LENS, PMD, EBF³)
- ☐ Sheet Lamination (LLM, LOM, LMP)
- ☒ Material Extrusion (FLM, FDM, MJS)
- ☐ Binder Jetting (3D-Printing, M³D)
- ☒ Material Jetting (MJM, PJM)
- ☐ Hybrid (CMB, UC)
- ☐ ________________

Research fields

- ☐ Build-up rates
- ☐ Build chamber volume
- ☒ Manufacturing costs
- ☒ Material properties (e.g. mechanical, electrical, thermal)
- ☒ Process tolerances
- ☒ Part tolerances
- ☒ Design rules
- ☒ Combining processes
- ☒ Product optimization
- ☐ ________________

Research profile



Rating scale:
0 = no research activity
1 = limited research activity
2 = average research activity
3 = increased research activity
4 = intensive research activity
5 = highly intensive activity

Number of covered fields
< 20
< 10
< 3

Current research projects

- Evaluation system for products manufactured by AM-Technologies and post-processes
- Conceptualization, design and implementation of a software-tool for recognition and evaluation of automation potential in hybrid assembly processes with regard to flexibility, economy and efficiency
- Basics of a quality assurance system applied to AM-processes
- Development of a picture based supervision system for additive Laser Beam Melting processes Multiple target optimization of the pre-process for quality assurance of parts built by Laser Sintering
- Layout and assembly of a partly automated powder-bed removal system with downstream powder handling in compliance with safety at work, ergonomics and productivity of powder-bed processes
- Knowledge-based support system for 3D-CAD-CAM-processes suitable for rapid manufacturing
- ...

Publications

Recent publications

- Baier, O.; Witt, G.: Application driven Process Chain for the Manufacturing of Fuel Cell Components consisting of Multi-Jet Modeling, Electroforming and Machining, Conference & Proceedings of the13th RAPDASA annual international Conference: Additive Manufacturing in Industry, Pilansberg, South Africa, 2012
- Sehrt, J.T.; Martha, A.; Witt, G.: Strategy for the manufacturing of perfused parts using Laser Beam Melting, Rapid Product Development Association of South Africa (RAPDASA), 31st Oct - 2nd Nov, 2012
- Keszczynski, S.; Sehrt, J.T.; Witt, G.; zur Jacobsmühlen, J.: Error Detection in Laser Beam Melting Systems by High Resolution Imaging, International Solid Freeform Fabrication Symposium, The University of Texas at Austin, August 6-8, 2012
- Wegner, A.; Witt, G.: Laser Sintered Parts with Reduced Anisotropy of Mechanical Properties, RAPID 2012 Conference, Atlanta, GA, USA, 22th - 25th May, 2012
- ...

Stakeholder

Overview stakeholder

Automotive industry	Machine manufacturer
Medical industry	Material supplier
Aerospace industry	Government
Electronics industry	Research institutes
Committees	Students

Industrial partners

- ISIS IC GmbH
- Daimler AG
- BMW AG
- Thyssen Krupp AG
- Siemens AG
- Contitech AG
- MTU Aero Engines
- Galavno-T GmbH
- SLM Solutions
- EOS Electro Optical Systems
- Concept Laser GmbH
- powerCUT GmbH
- NRU GmbH
- IWF GmbH
- Olympus AG
- ...

Value proposition

- Application oriented research

Research partners / Networks

- Center for Fuel Cell Technology GmbH, Duisburg
- Research Institute for Precious Metal and Metals Chemistry, Schwäbisch Gmünd
- InnovationAllianz of NRW Universities
- VDI Committee on Rapid Prototyping
- Netzwerk Strahlschmelzen
- RWTH Aachen
- Ruhr Universität Bochum
- Universität München
- Beckmann Institut
- TU Dresden
- TU Chemnitz
- Fraunhofer Institutes

Value proposition

- Knowledge transfer
- Education of future AM-engineers

Services rendered

- Analysis and optimization of production/assembly processes and seamless process chains
- Feasibility studies
- Benchmark and consulting
- Training courses and seminars regarding additive manufacturing

Figure 2-14: Detailed profile of the Rapid Technology Center

2.1.14 The University of Sheffield

University of Sheffield: Advanced Additive Manufacturing (AdAM)

Short description of the institute

The University of Sheffield conducts AM R&D across a wide range of disciplines. AM activity is performed under a number of different centers (including The Mercury Centre and The Advanced Manufacturing Institute), within different departments (including Mechanical Engineering, Materials Science and Engineering, Civil and Structural Engineering and The School of Clinical Dentistry) and through consultancy and spin out companies (including Limit-State). Collectively, AM activity across the University comes under the name "Advanced Additive Manufacturing" (AdAM).

For more information on The Mercury Centre visit: www.mercurycentre.org.

Contact

Prof. Neil Hopkinson
Department of Mechanical Engineering
The University of Sheffield
S1 3JD
United Kingdom

Categorization

Basic research | **Applied research** | Service

Resources

AdAM activities are funded by various sources including EPSRC, ERDF, EOARD, medical charities and industry

The Mercury Centre has secured £5 million of funding including significant AM activity

Employees

As at June 2012 there are ~15 academics and managers and 40-50 PhD students and researchers that are active in AM.

Equipment (machines, measurement equipment etc.)

- Electron Beam Melting (Arcam S2 x 2)
- Selective Laser Melting (Renishaw 250)
- Electron Beam Welder (ProBeam E40)
- Microscale Printer (Optomec Aerosol Jet 300 CE)
- Laser Sintering (EOS P100)
- High Speed Sintering (non commercial)
- Inkjet/curing (Objet Eden 260V)
- Inkjet experimental (MicroFab JetLab IV)
- Micro-stereolithography (experimental x 4)
- Range of analysis and testing equipment

Goals

- Manufacturing processes including the modification of existing processes (including high temperature Selective Laser Melting) and the invention and subsequent development of new processes (including High Speed Sintering and Anchorless Direct Metal Additive Manufacturing)
- Materials (metals, polymers, ceramics and composites) using a wide range of approaches from Electron Beam Melting to micro-stereolithography and inkjet methods.
- Applied inkjet printing (using inkjet printing as an AM technique)
- Design Tools including the development of software for automatic design optimization.
- Medical and dental applications including the creation of customized implants and soft tissue prostheses

Vision

AdAM seeks to build on expertise across a range of different disciplines in order to maximize the befits that can be brought to field of AM. Areas of R&D include manufacturing processes, materials science, design tools and applications across a range of sectors including healthcare, aerospace and consumer products. Aligned to the University's, strategic focus on Manufacturing, AdAM is committed to conducting basic research from the pure sciences (including Polymer Chemistry) through to industrial applications through vehicles such as The Mercury Centre, The Polymer Centre and the Advanced Manufacturing Institute.

Focal point of research

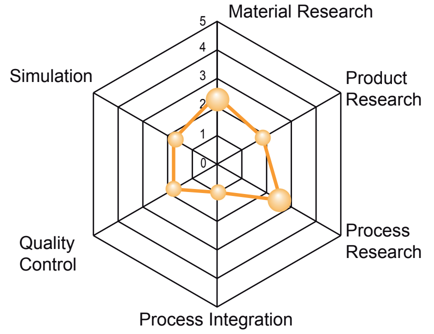
Applied technologies

- ■ Powder Bed Fusion (LS, SLM, LC, MS)
  - ☒ Plastic-based
  - ☒ Metal-based
  - ☒ Ceramic-based
- ☒ Polymer Vat (SL, µSL, DLP)
- ☒ Directed Energy/Metal Deposition (LENS, PMD, EBF³)
- ☐ Sheet Lamination (LLM, LOM, LMP)
- ☐ Material Extrusion (FLM, FDM, MJS)
- ☒ Binder Jetting (3D-Printing, M³D)
- ☒ Material Jetting (MJM, PJM)
- ☐ Hybrid (CMB, UC)
- ☒ Anchorless SLM (ASLM)

Research fields

- ☒ Build-up rates
- ☒ Build chamber volume
- ☒ Manufacturing costs
- ☒ Material properties (e.g. mechanical, electrical, thermal)
- ☒ Process tolerances
- ☒ Part tolerances
- ☐ Design rules
- ☐ Combining processes
- ☒ Product optimization
- ☐ ________________

Research profile



Rating scale:
0 = no research activity
1 = limited research activity
2 = average research activity
3 = increased research activity
4 = intensive research activity
5 = highly intensive activity

Number of covered fields
< 20
< 10
< 3

Current research projects

- Anchorless Selective Laser Melting (ASLM) of high melt temperature metals
- Microstructural Evolution in Shaped Metal Deposition (SMD)
- Additive Manufacture of structural components for automotive and aerospace applications
- Net Shape Manufacture and behavior of complex materials and components : Additive Layer Manufacture using Laser and Electron Beam processes; Aerosol Jet Technologies
- Additive Layer Manufacture of structural components for automotive and aerospace applications
- Microlattices with Auxetic behavior fabricated by Electron Beam
- Developing fast melt themes to increase productivity and reliability of EBM
- Microlattices with Auxetic behaviour fabricated by Electron Beam Melting
- Studying the influence of processing parameters on mechanical properties of EBM deposited material
- Microstructural evolution and control of aerospace and automotive alloys using selective laser melting and electron beam melting
- Opening up the range of thermoplastic polymers for additive manufacturing
- ...

Publications

Recent publications

- Tyas, A.; Pichugin, A.V.; Gilbert, M.: Optimum structure to carry a uniform load between pinned supports: exact analytical solution. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 467 (2128), April, 2010, p. 1101-1120
- Plummer, K.; Vasquez, M.; Majewski, C.E.; Hopkinson, N.: Study into the recyclability of a thermoplastic polyurethane powder for use in laser sintering. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2012
- Hopkinson, N.; Hague, R.M.J.; Dickens, P. M.: Rapid Manufacturing: An Industrial Revolution for the Digital Age. John Wiley and Sons Ltd, 2005
- Majewski, C.E.; Hopkinson, N.: Effect of section thickness and build orientation on tensile properties and material characteristics of laser sintered nylon-12 parts. In: Rapid Prototyping Journal, 17(3), 2011, p. 176-180
- ...

Stakeholder

Overview stakeholder

Automotive industry	Machine manufacturer
Medical industry	Material supplier
Aerospace industry	Government
Electronics industry	Research institutes
	Students

Industrial partners

- Unilever
- BAE Systems
- EADS
- Xaar

Value proposition

- A well connected group of interdisciplinary researchers covering a broad spectrum of expertise to deliver value to a wide range of sectors.
- Providing access to the latest innovative manufacturing technology and materials to reduce costs, add functionality and achieve improved commercial value.

Research partners / Networks

- Mercury Center
- University of Sheffield Polymer Centre
- Institute for Microstructural and Mechanical Process Engineering (Immpetus)
- Advanced Manufacturing Research Centre (AMRC)
- University of Sheffield Advanced Manufacturing Institute
- University of Louisville
- Loughborough University
- University of Manchester

Value proposition

- Training of postgraduate and postdoctoral researchers in advanced manufacturing techniques
- Publications, presentations and other activities for disseminating the knowledge and understanding of AM.

Services rendered

- Delivery of consultancy plus research and development projects and programs.
- Seminars through the Polymer Centre and The Mercury Center

Figure 2-15: Detailed profile of the W.M. Keck Center for 3D Innovation

2.1.15 W.M. Keck Center for 3D Innovation

W.M. Keck Center for 3D Innovation

Short description of the institute

The W.M. Keck Center for 3D innovation is located at the University of Texas at El Paso. With more than $5 million in research infrastructure, it represents a premier biomedical, engineering, and advanced manufacturing facility focused on multi-disciplinary biomedical, materials, and manufacturing research, capable of creating three-dimensional anatomical models to aid surgeons and medical researchers and a wide range of fabrication technologies called as Functional Integrated Layered Manufacturing, or FILM.

The SPEC Center will be co-directed by Professor of Mechanical Engineering Ryan Wicker, Ph.D., the current director of the Keck Center.

Contact

Prof. Ryan Wicker
Francisco Medina
W.M. Keck Center for 3D Innovation
University of Texas at El Paso
Engineering Building Room 108
El Paso 79968, Texas
Web: www.utep.edu/wmkeck

Categorization

Basic research | Applied research | Service

Goals

The specific aims of the center include:

- Decrease product development time and overall time to market
- Decrease costly mistakes in design
- Test product functionality prior to production
- Minimize number of engineering design changes
- Eliminate undesirable features early in design
- Improve technical and sales communications
- Directly manufacture end-use products

Vision

From surgical models to tissue engineering to product prototypes, the Keck Center is ready to transform ideas into three dimensions. In addition to basic research, the Keck Center for 3D innovation offers services to medical and manufacturing industries and other customers who need solutions in design and fabrication. The Center is dedicated to assist and to provide companies competitive advantages through access to state-of-the-art facilities and expertise.

Ressources

The University of Texas at El Paso was awarded a $1 million grant from the W.M. Keck Foundation to establish the W.M. Keck Border Biomedical Manufacturing and Engineering Laboratory in the College of Engineering

No further specification

Employees

3 Administrators

3 Administrative staff

4 doctoral candidates

4 graduate students

Equipment (machines, measurement equipment etc.)

- Stratasys FDM Maxum and Titan
- Objet Eden 333 (3DP)
- 3D Systems Sinterstation 2000 (SLS)
- 3D Systems Stereolithography (SL)
- UTEP Patent Pending Multi-Material SL
- Hybrid Direct Write/SL
- Desktop Engine 3D portable scanner

Focal point of research

Applied technologies

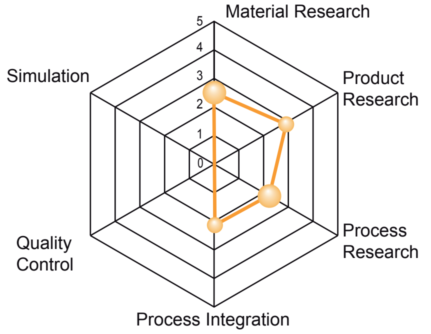
■ Powder Bed Fusion (LS, SLM, LC, MS)
- ☒ Plastic-based
- ☒ Metal-based
- ☐ Ceramic-based

☒ Polymer Vat (SL, µSL, DLP)
☐ Directed Energy/Metal Deposition (LENS, PMD, EBF³)
☐ Sheet Lamination (LLM, LOM, LMP)
☒ Material Extrusion (FLM, FDM, MJS)
☒ Binder Jetting (3D-Printing, M³D)
☐ Material Jetting (MJM, PJM)
☐ Hybrid (CMB, UC)
☐ ______________

Research fields

☐ Build-up rates
☐ Build chamber volume
☒ Manufacturing costs
☒ Material properties (e.g. mechanical, electrical, thermal)
☒ Process tolerances
☒ Part tolerances
☐ Design rules
☐ Combining processes
☐ Product optimization
☒ Biomedical/-active products

Research profile



Rating scale:
0 = no research activity
1 = limited research activity
2 = average research activity
3 = increased research activity
4 = intensive research activity
5 = highly intensive activity

Number of covered fields: < 20, < 10, < 3

Current research projects

Research focus: Biomedical engineering
- Three-dimensional anatomical models to aid surgeons and medical researchers
- Creating bio-active „scaffolds“ that give engineered tissue a place to live and grow
- Imaging, modeling and manufacturing of cardiovascular hemodynamics
- Tissue engineering

Research focus: Functional manufacturing
- Functional Integrated Layered Manufacturing (FILM)
- 3D Electronics, MicroElectroMechanical Systems (MEMS)
- (functional) Rapid Prototyping of miniature RF relays, aperture masks for an imaging spectrometer, cardiovascular system models and other three-dimensional electronics
- Micro Fabrication
- Advanced Materials
- Rapid Tooling

Projects
- Stereolithography of Multi-Lumen, Multi-Material Bioactive Nerve Guidance Conduits

Publications

Recent publications
- Choi, J.W.; Kim, H.C.; Wicker, R.: Multi-Material Stereolithograpy. under review Journal of Materials ProcessingTechnology, 2009
- Choi, J.W.; Yamashita, M.; Sakakibara, J.; Kaji, Y.; Oshika, T.; Wicker, R.: Combined Micro and Macro Additive Manufacturing of a Swirling fow Coaxial Phacoemulsifier Sleeve with Internal Micro-Vanes. under review Biomedical Microdevices, 2009
- Choi, J.W.; Quintana, R.; Wicker, R.: Fabrication and Characterization of embedded horizontal micro-channels using line-scan stereolithography. under review Rapid Prototyping Journal, 2009
- ...

Stakeholder

Overview stakeholder

Automotive industry	Machine manufacturer
Medical industry	Material supplier
Aerospace industry	Government
Electronics industry	Research institutes
Committees	Students

Industrial partners
- Sentrx Surgical, Inc

Value proposition
- Providing high quality rapid prototyping and rapid production services to fit the needs of the customers
- Transforming ideas into three dimensions

Research partners / Networks
- University of Texas at El Paso
- National Science Foundation
- The University of Texas System
- Structural and Printed Emerging Technologies (SPEC) Center
- Sandia National Laboratories
- University of Utah
- Utah State University
- Stanford University
- University of New Mexico COSMIAC
- North Carolina State University
- University Hospitals of Cleveland
- Musculoskeletal Mechanics and Materials Laboratories

Value proposition
- Education
- Knowledge dissemination

Services rendered
- Rapid prototyping, 24-hour rapid tooling and tool design
- Reverse engineering, from surgical model to design
- Engineering and rapid manufacturing
- Short-run production

Figure 2-16: Detailed profile of the Fraunhofer Institute for Manufacturing Technology and Advanced Materials

2.2 Research Fields

The research fields were clustered to 6 categories.

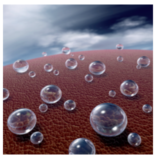
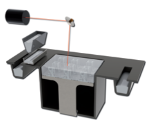
To create the AM Research Map, the research landscape was segmented in a first step. Therefore, initially the requirements deduced in the preceding project were allocated to research fields. All in all, 43 research fields were identified. These were clustered to 6 categories:

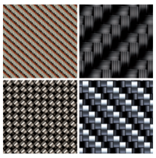
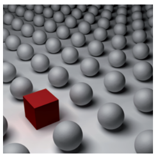
- Material Research,
- Product Research,
- Process Research,
- Process Integration,
- Quality Control and
- Simulation.

The following sections comprise an overview on the research fields for each category.

2.2.1 Material Research

The research field *material research* encompasses research on development of new materials as well as understanding and advancement of existing materials. Research in this field also involves the analysis of material properties and material processing in order to realize required property profiles. In addition, research incentives on facilitating the production and processing of industrial materials are addressed. An overview is provided in figure 2-17.

1: Functional Materials	
	The research focuses on the development of materials with particular characteristics, properties and functions which are normally inherent to the material. Exemplary functional materials are shape memory alloys. Shape memory alloys “remember” their original geometry and recover to the initial shape by exposing them to e.g. heat after deformation.
2: Temperature Resistance	
	The research focuses the analysis of the temperature resistance of materials – resistance against very high or low temperatures. Amongst other things, this includes the development of materials with high melting points. These materials allow a deployment in challenging environments. Another focal point is the reduction of high-temperature creep in industrial alloys.
3: Material/Powder Generation Process	
	The research field encompasses the analysis of monomer molecules and investigations of powder generation processes. The goal is to improve those processes and/or to create new generating processes.

4: New Materials	
	This research field entails all measures revolving around developing and utilizing new materials for AM. This counts for completely newly invented materials and/or for the advancement of existing materials through enhancement of their properties/characteristics.
5: Material Quality	
	The research aims at understanding the characteristics which essentially influence material quality. Thereby, sustained reproducibility and a persistently high level of material quality are sought. This encompasses analyses of particle sizes, purity of materials, stability, temperature resistance, layer size etc.
6: Viscosity / Rheological Properties	
	Research comprises investigations on the viscosity and rheological properties of materials to obtain information about the flow ability, particle properties, their distribution and particle morphology.
7: Microstructure Manipulation	
	The research in this research field aims at the determination of the impact different production parameters may have on the microstructure. This encompasses analyses of melting processes and the development of methods for changing and manipulating characteristics during the sintering process.
8: Material Costs	
	The research strives for the reduction of material cost for AM. Possible approaches are aspects such as the optimization of the material production and recycling processes, and the reduction of material consumption.
9: Ageing Properties	
	The research focuses the analysis and determination of the ageing behavior of materials. With regard to AM, the aging behavior describes how characteristics (e.g. material properties, dimensional deviations etc.) or the quality of the produced parts change over time.
10: Mechanical Properties	
	The research focuses on the retrieval and enhancement of mechanical characteristics of materials, e.g. the bending stiffness of a part. The analysis and enhancement of mechanical properties can contribute to increase the product quality. The research includes static and cyclic testing of material specimen under varying conditions.

11: Electric Properties	
	The research field focuses on the analysis, determination and development of electric material properties, e.g. increasing the conductivity of different materials.
12: Thermal Properties	
	The research aims at the investigation, determination and improvement of the thermal material behavior – in particular, that means the behavior of materials at different temperatures, e.g. the expansion of parts under temperature influence.

Figure 2-17: Overview of research fields from the category Material Research considered in the AM Research Map (pictures courtesy of: see picture credits on page 137)

2.2.2 Product Research

Product research focusses on broadening the understanding of product costs against the background of a product's life cycle. It comprises the extension of knowledge about product technologies, such as lattice structures, gradient structures etc., and includes attempts pushing forward the standardization of construction. Figure 2-18 shows the research fields considered in this field.

1: Design Rules	
	The research focuses on the development of design rules that are required for standardized construction of additively manufactured parts. Standardized design rules facilitate the production of parts with a constant quality. This is a necessity for mass production.
2: Bionic Structures	
	This research field entails the implementation of biological structures into products. Bionic structures include principles found in biology – usually these have been brought to perfection by billions of years of evolution. Using these principles entails a huge potential to increase the part/product performance. Many of these parts are applied for implants, e.g. for human bones.
3: Life Cycle Costs	
	The research follows the trend of increasing awareness for an all-encompassing life cycle approach. This means cost management from the development of the product until the retraction of the product from the market. The goal is a reduction of life cycle costs which can be achieved by e.g. comparing integral and differential part construction.

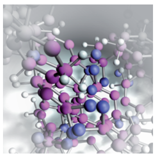
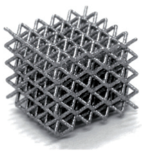
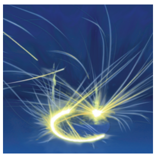
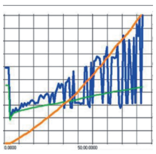
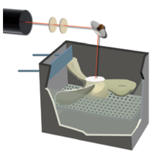
4: Recycling Costs	
	The research in this field investigates material recycling processes and how these processes could potentially be optimized. An exemplary approach is the improvement of the recyclability of residual powder, since usually huge amounts of residual powder remain after production.
5: Light Weight Structures	
	The research focuses on the development of light-weight structures. These structures unite high stiffness and low weight, and thus offer a huge potential for different applications and further research.
6: Gradient Structures	
	The research focus is the development of structures providing different material properties in different areas.
7: Part Tolerances	
	The research focuses on the improvement of part tolerances in order to improve the characteristics of a product and increase part reproducibility. This counts for the optimization of the parts' surface quality and dimensional accuracy. Meeting both characteristics is oftentimes core-requirement for large-scale production.
8: Lattice structures	
	The research on lattice structures focuses on the analysis and enhancement of these beam-type structures as well as on their construction by particular software.

Figure 2-18: Overview of research fields from the category Product Research considered in the AM Research Map (pictures courtesy of: see picture credits on page 137)

2.2.3 Process Research

Research in this field deals with improving the processes involved in AM, exploring the capabilities of multi material manufacturing, tackling the challenge of build chamber restrictions and increasing the production speed by raising build-up rates. It also involves the development of required software solutions. An overview is provided in figure 2-19.

1: Energy Consumption	
	The field energy consumption deals with the development of more efficient production processes in order to reduce production costs and increase environmental compatibility.
2: Laser Development	
	The research field focuses on the adaption of conventional laser technologies and/or on the development of new laser technologies in order to accelerate and improve production processes. Thereby, the efficiency increases – another important step on the path towards DM.
3: Multi Material Manufacturing	
	The research in multi material manufacturing focuses on the development of AM-processes that enable the processing of different materials by a single AM-machine (sequential processing) or the processing of different materials within one job (simultaneous processing).
4: Process Tolerances	
	The research focuses on the investigation and understanding of parameters influencing process tolerances with the goal to develop approaches to increase process stability and reliability.
5: Machine Costs	
	The research on machine costs aspires the reduction of the overall machine costs. This can be achieved by e.g. optimization of the machine design to lower machine maintenance costs and production costs.
6: Build Chamber Volume	
	This research field deals with the development of AM-machines that feature bigger build chambers in order to increase the range of possible AM applications.
7: Temperature Management	
	The research on temperature management focuses on the improvement of temperature control processes to realize parts with perfectly homogeneous properties and higher stability. Temperature control is a pivotal lever for the successful creation of high-quality AM-parts.

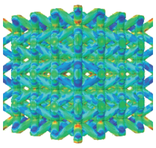
8: Build-up Rates	
	This research field focuses on the acceleration of AM-processes, while preserving a constantly high part quality.
9: Residual Stresses	
	The research on residual stresses copes with the analysis of residual stresses in AM-parts and the development of methods on how to reduce them.
10: Software Development	
	The research in this field deals with the development of new software solutions for different steps within the process chain, e.g. CAD-software or solutions for monitoring and controlling tasks.

Figure 2-19: Overview of research fields from the category Process Research considered in the AM Research Map (pictures courtesy of: see picture credits on page 137)

2.2.4 Process Integration

Research in these fields deals with the integration of AM into conventional production, joining different technologies to a coherent processes. Improving the degree of automatization and curing/post-processing methods are also included, see figure 2-20.

1: Combining Processes	
	Research is conducted on approaches for combining different technologies. This counts for the combination of different AM-technologies and for pairing of AM-technologies with existing manufacturing technologies as well.
2: Post-Treatment / Costs for Post-Processing	
	The research on post-treatment and costs for post-processing focuses on the development of new post-production processes and on the improvement of conventional post-production processes with the goal to reduce costs for post processing and reducing detrimental effects of post-processing on the party quality.
3: Process Automatization	
	The research in this field focuses on the development of approaches for the automatization of AM-processes with the goal to realize highly automated production processes from the material filling to post-processing. This also includes the development of particular software solutions.

4: Supply Chain Optimization	
	The improvement of the supply chain organization focuses on the one hand on the optimization of the material flow from the material suppliers to the delivery of the end-product. This encompasses all (not necessarily AM-specific) logistics steps, such as the provision of powder on time etc. On the other hand, the supply chain for AM-technologies may differ from conventional manufacturing technologies. There are two different approaches conceivable: (1) parts are manufactured in a centralized production and transported to their final destination; (2) the file is sent to its destination and produced (decentralized) on its final destination.
5: Integration of AM into existing Manufacturing Processes	
	The research focuses on the development of approaches for the integration of AM-technologies into conventional manufacturing processes in order to facilitate series production with AM-technologies.

Figure 2-20: Overview of research fields from the category Process Integration considered in the AM Research Map (pictures courtesy of: see picture credits on page 137)

2.2.5 Quality Control

In this category, inter alia research on uniform certifications of products and processes and establishing standardized testing routines is performed. It also comprises enhancing AM-specific quality control measures and implementing them into the production process. An overview is provided in figure 2-21.

1: Product Certification	
	The research in this field deals with the development of standardized certification guidelines for AM-parts in order to accelerate certification processes.
2: Process Certification	
	The research in this field focuses on the development of standardized certification guidelines for AM-processes in order to accelerate certification processes.
3: Standards Development for Testing Procedures	
	The research in this research field focuses on the development of procedures for standardized testing of AM-machines and additively manufactured parts.

4: Quality Control	
	The research in this field focuses on the development and improvement of quality control processes. This includes process and part control processes as well as quality reporting processes.
5: Online Process Control	
	The research deals with the development of real time control processes, for instance via sensors or software. These processes are an important enabling factor on the path to efficient series production.

Figure 2-21: Overview of research fields from the category Quality Control considered in the AM Research Map (pictures courtesy of: see picture credits on page 137)

2.2.6 Simulation

The category *simulation* involves research on the Finite Element simulation of parts and materials, as well as virtualizing the entire production process, see figure 2-22.

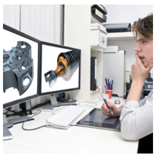
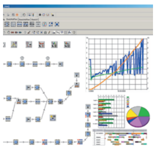
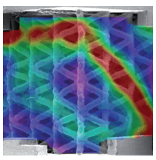
1: Simulation of Parts	
	The research field focuses e.g. on the Finite Element simulation of AM-parts.
2: Simulation of Processes	
	The research in this field focuses on the simulation of AM-processes to reduce the risk of errors within the process.
3: Simulation of Materials	
	The research on material simulation focuses on the creation of Finite Element material models to simulate the behavior of AM-materials.

Figure 2-22: Overview of research fields from the category Simulation considered in the AM Research Map (pictures courtesy of: see picture credits on page 137)

2.3 Inventory of Selected Additive Manufacturing Technologies

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

2.3.1 Fused Layer Modeling Technologies

Fused Layer Modeling (FLM) is an additive technique using a thermoplastic material. An extrusion head selectively deposits the molten thermoplastic filament to create each layer with a particular tool path. Through thermal fusion, the material bonds with the layer beneath and solidifies, thus forming a permanent bond between two layers. Directly after the deposition the material hardens [AST12]. Fused Deposition Modeling (FDM) by Stratasys, Inc. is one example for FLM Technologies [Str13b-ol]. The principle of the process is visualized in figure 2-23. Figure 2-24 presents the characteristics of FDM, specifying process and material data. For more information see [Str11b-ol], [Alp13a-ol], [Str11c-ol], [GRS10], [Geb12]. The technical and material data refer to the Stratasys FORTUS 400mc system [Str09a-ol].

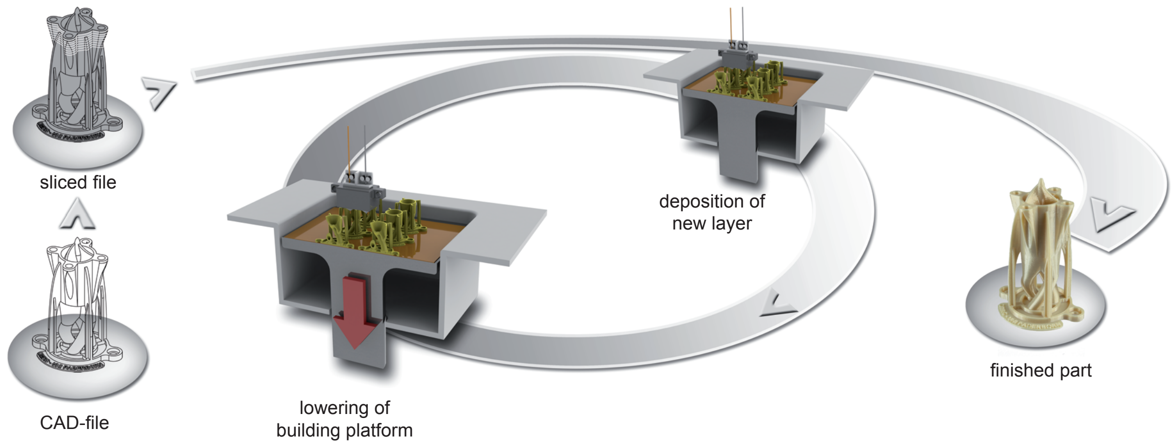


Figure 2-23: Process principle of Fused Deposition Modeling (picture courtesy of DMRC)

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

Fused Deposition Modeling (FDM)

Short Description

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

Technical Data*

Accuracy: +/- 127 µm

Support structures: necessary

Building speed: material and parameter dependent

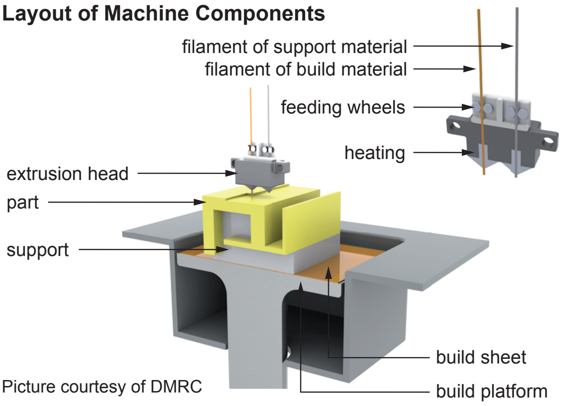
Build Materials

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

Principle of Layer Generation

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

Layout of Machine Components



Picture courtesy of DMRC

Build Chamber Volume

The spectrum of FDM machines is wide ranging from small, low-cost machines to larger, more expensive machines that are adaptable and highly sophisticated. FDM Fortus 900mc has the biggest build chamber volume measuring (x/y/z in mm) 600/500/600 mm.

Build Time and Build-up Rate

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

Surface Quality and Accuracy

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

Material

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

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

Data Format/Software

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

Post-Processing

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

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

Figure 2-24: Characteristics of Fused Deposition Modeling

Most geometries require supports which have to be removed in a post process [Str13a-ol], [Str13b-ol] [Alp13a-ol], [Str11c-ol], [Str09a-ol].

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

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

2.3.2 Powder Bed Fusion Plastic Technologies

Powder Bed Fusion (PBF) Plastic Technologies represent an additive manufacturing technique in which powdered plastic materials are selectively sintered. The energy to locally fuse the powder is performed by a laser beam. After all layers are built, the part can be removed from the powder bed. The remaining powder is reusable for future production builds after being blended with new powder [AST12]. An exemplary technology is Laser Sintering (LS) by EOS GmbH Electro Optical Systems [Eos13a-ol]. The process principle of LS is visualized in figure 2-25. Figure 2-26 presents the characteristics of the LS technology, specifying process and material data [Eos12-ol], [Eos13a-ol], [Eos13b-ol], [Eos13c-ol], [Eos13d-ol], [GRS10], [Geb12]. The data refers to the EOSINT P395.

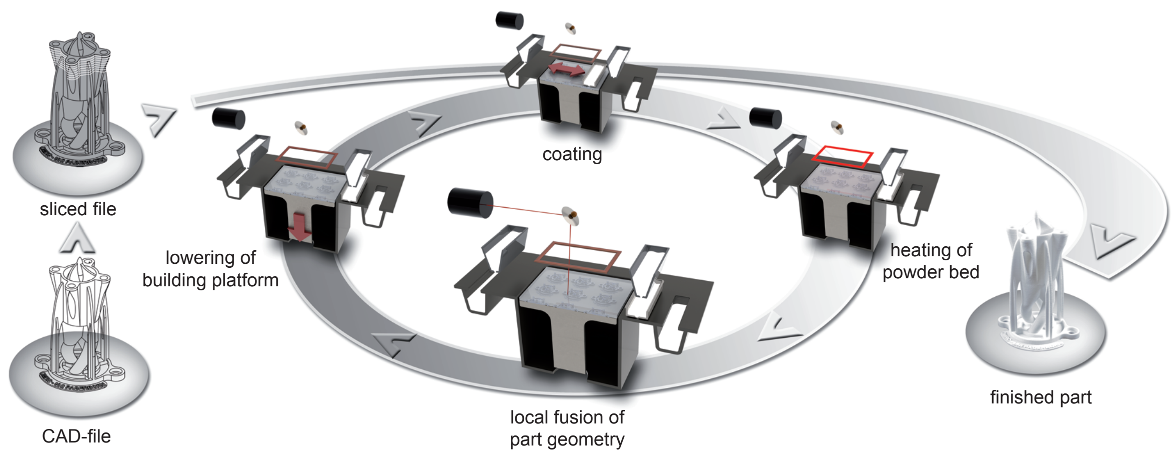


Figure 2-25: Process principle of Laser Sintering (picture courtesy of DMRC)

Via LS, three dimensional objects of any shape can be built without restrictions on forming tools. Parts can have integrated functions like moving elements or inner structures. Ideal applications for LS are highly complex parts in low-volume production. LS technology is used for manufacturing prototypes, models and end-use products. Due to the huge variety of materials, the method is predestined to be used in the tooling industry, aerospace industry, automotive industry, architecture, and in the consumer goods industry.

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

Laser Sintering (LS)

Short Description

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

Technical Data*

Layer thickness: 60-180 µm

Laser type: 50 W CO_2 Laser

Scanning speed: 6000 mm/s

Support structures: not necessary

Building speed: 35 mm/h

Build Materials*

e.g. PA2200 (basis: nylon 12)

Melting temp.: ≈ 186 °C

Recrystallis. temp.: ≈ 140 °C

Particle size $d_{V,50}$: ≈ 55 µm

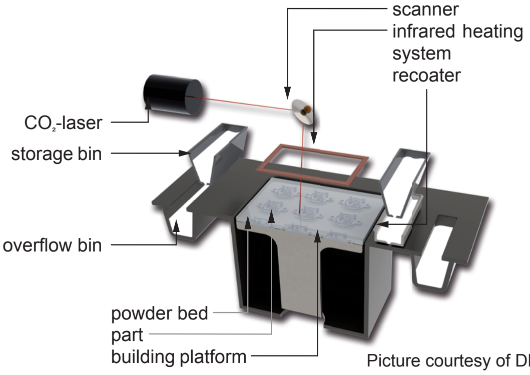
Part. size distrib.: ≈ 3-100 µm

Tensile strength: 48 N/mm^2

Principle of Layer Generation

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

Layout of Machine Components



Picture courtesy of DMRC

Build Chamber Volume

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

Build Time and Build-up Rate

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

Surface Quality and Accuracy

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

Material

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

Data Format/Software

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

Post-Processing

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

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

Figure 2-26: Characteristics of Laser Sintering

Advancements in the processing of bio-compatible, high-performance materials recently gave rise to a number of new applications, especially in the medical industry [Eos13a-ol].

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

Current research initiatives focus the analysis of material properties and material processing in order to realize the required property profiles.

Research initiatives focus material properties and processing.

2.3.3 Powder Bed Fusion Metal Technologies

Using Powder Bed Fusion (PBF) Metal Technologies, powdered metal material is selectively melted layer by layer via lasers or electron beams. In the process, the powder bed fuses through solidification [AST12], [GRS10]. Selective Laser Melting (SLM) by SLM Solutions GmbH is one example for Powder Bed Fusion Metal Technologies [Slm13a-ol]. Figure 2-27 illustrates the principle of the SLM process; figure 2-28 presents the characteristics, specifying process and material data. The data refer to the SLM Solutions 250HL system. For more information see [Slm13a-ol], [Slm13b-ol], [Slm13c-ol], [GRS10], [Geb12].

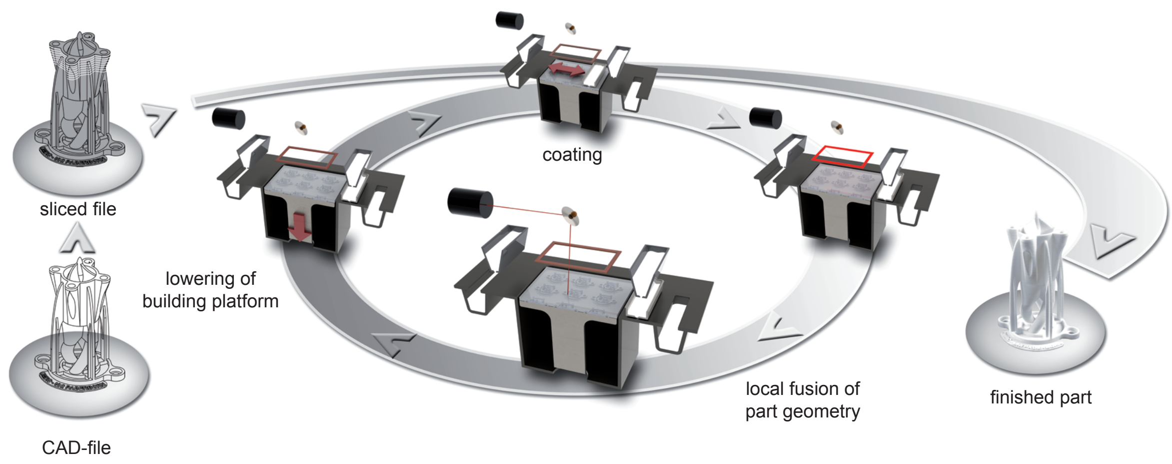


Figure 2-27: Process principle of Selective Laser Melting (picture courtesy of DMRC)

Unlike machined parts, SLM parts can have thin walls, deep cavities or hidden channels. Parts with high toughness, high strength and good thermal conductivity can be produced. As the weight of the part is heavy and the heat has to be dissipated, support structures are necessary. High thermal gradients can lead to residual stress or to the cracking/failure of the part [GRS10], [Geb12].

Selective Laser Melting (SLM)

Short Description

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

Technical Data*

Layer thickness: 20-100 µm

Laser type: Ytterbium laser 400/1000 Watt

Scanning speed: 20000 mm/s

Support structures: necessary

Bulding speed: 25 cm^3/h

Build Materials

Titanium, Aluminium

Tool/Stainless steel

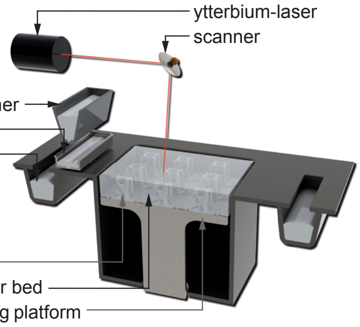
Alloys depending on the application

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

Principle of Layer Generation

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

Layout of Machine Components



Picture courtesy of DMRC

Build Chamber Volume

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

Build Time and Build-up Rate

The build time depends on the layer thickness and the processed material. With finer layers, more accurate parts can be produced; higher layers however require stronger laser modules. On average, build times are 7-30 cm³/h for SLM. In general powder bed fusion processes take longer for part construction than other AM-processes due to the pre-heat and cool-down cycles involved.

Surface Quality and Accuracy

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

Material

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

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

Data Format/Software

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

Post-Processing

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

* Technical data refer to SLM Solutions 250HL

Figure 2-28: Characteristics of Selective Laser Melting

SLM technology is used for functional testing of production quality prototypes as well as for manufacturing of complex end-use parts in low-volume, and for building highly complex organic structures. In addition, SLM is broadly applied to produce light-weight and lattice structures. Due to the technology's inherent geometric complexity benefits and excellent material properties, many industries have been benefiting from this technology, e.g. the automotive, aerospace, tooling, jewelry and the medical industry [Ren13-ol], [Rea11-ol] [Slm13d-ol].

SLM is widely used for light-weight structures.

Current research initiatives aim at the development of new materials as well as understanding and advancement of existing materials. This also comprises the analysis of material properties and material processing in order to realize required property profiles, facilitating the production and processing of industrial materials.

2.3.4 Polymerization Technologies

Polymerization is an additive technique used to produce parts from photopolymer materials. The photopolymer material is in a liquid state. By using a laser beam the material is curing or solidifying layer by layer. The process can harden the material in a predetermined thickness. Stereolithography (SLA) is one example for Polymerization Technologies [AST12]. Figure 2-29 illustrates the process principle of SLA technologies; the characteristics, specifying process and material data are presented in figure 2-30. The data refer to the iPro 9000XL SLA Center by 3D Systems Corporation. For more information see [3ds13a-ol], [3ds13b-ol], [3ds13c-ol], [Alp13b-ol], [CCD+11-ol], [Par13b-ol].

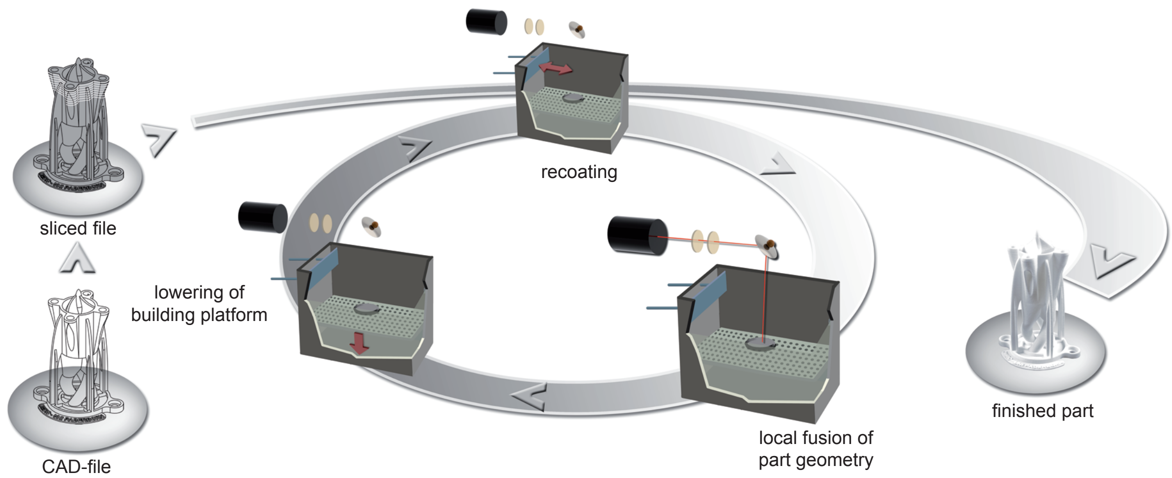


Figure 2-29: Process principle of Stereolithography (picture courtesy of DMRC)

SLA parts provide high accuracy and smooth surfaces. There is a great variety of materials that can be processed via SLA, mimicking the look and feel of most engineering plastics, e.g. Polypropylene, Polycarbonate and ABS.

Stereolithography (SLA)

Short Description

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

Technical Data*

Laser Type: Nd:YV04

Layer thickness: 50-150 µm

Accuracy: +/- 25-50 µm

Support structures: necessary

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

Build Materials*

e.g. Accura ® Peak ™Amber

Liquid Density: 1.32 g/cm

Solid Density: 1.36 g/cm³

Viscosity: 605 cps

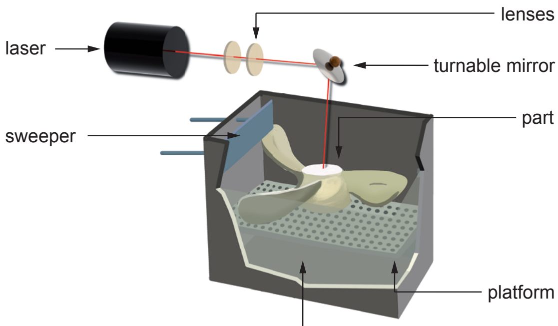
Penetration Depth: 5.6 mils

Critic. Exposure 11.5 mJ/cm²

Principle of Layer Generation

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

Layout of Machine Components



Picture courtesy of DMRC

Build Chamber Volume

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

Build Time and Build-up Rate

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

Surface Quality and Accuracy

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

Material

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

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

Data Format/Software

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

Post-Processing

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

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

Figure 2-30: Characteristics of Stereolithography

These materials provide properties like thermal resistance, stiffness, flexibility and transparency to meet prototyping, testing and application needs.

SLA technology is used in many industries.

Today, SLA parts are widely used for rapid prototyping and partly for DM in a huge variety of industries, including the medical, military, electronics, automotive and consumer goods industry. Exemplary applications are patterns for injection molding core and cavity inserts, thermoforming, sand casting, blow molding, and various metal casting processes [3ds13d-ol]. Current research initiatives focus on the development of new materials and the advancement of the laser technology to accelerate production processes.

2.4 Additive Manufacturing Research Map

The data for the development of the Research Map was collected in a survey.

The data for the development of the AM Research Map was collected in a survey conducted in 2012. The object was to determine the research activity and intensity in the research landscape.

Structure and Proceeding in the Survey

The survey was conducted in English, addressing the institutes that were selected to be represented in the AM Research Map. To minimize the effort of completing the survey by the participants, it was structured in a multi-level way.

The first level of the poll asked the participants to provide personal information – name, name of the respective research institute, budget, and amount of staff. This sensitive data is required for measuring the intensity of research by comparable and neutral indicators. The overall budget allocated to each research field and the amount of staff are – among others – very meaningful indicators. In order to relativize both values for each research field, it was necessary to ask for the total budget and staff.

Firstly, the institutes indicated the research fields they are active in.

On the second level, the participants were asked to indicate in which research fields they are active in at all. Overall they were able to choose from the 43 research fields in 6 different categories, see chapter 2.2. Thereby, the participants indicated that the institute was basically active in a specific research field.

The third level of the survey entailed the actual assessment of the respective institutes' research intensity. For each of the indicated research fields, the institutes were asked to provide the following key performance indicators (KPIs):

Secondly, the institutes provided information on key performance indicators measuring the research intensity.

- Which AM-technology is addressed in the research field?
- Which annual budget is approximately allocated to this research field?
- How many staff has been working on this research field?
- How many projects have been pursued in this research field in the last 3 years?

- How many publications in this research field did you publish in the last 3 years?

The necessity of a multi-level survey automatically becomes evident. Without generically checking the research activity in level two, the participant would have had to answer these KPIs for each of the 43 research fields, regardless of whether he is active there or not.

Eventually, the answers to the KPIs were evaluated and assembled to a total degree of intensity for each technology-research-field-combination the institutes are active in. As the KPIs give it away, not only amount of staff and budged played a role, but also the total amount of recent projects and publications. Based on the collected data set, the AM Research Map was developed in a next step.

Structure of the Additive Manufacturing Research Map

Figures 2-32 and 2-33 show the AM Research Map. The Research Map is basically a table, indicating the research intensity for the 15 listed institutes at the top (columns) within the six research categories at the left side (rows). The table distinguishes the institutes according to the technologies they address (columns) and the research categories regarding the research fields (rows).

Each cell of the Research Map defines one technology-research-field-combination for a specific institute.

Thereby, each cell of the Research Map defines one technology-research-field-combination for a specific institute. The coloration of the cells indicates the intensity of the research activity within one technology-research-field-combination of the analyzed institutes. Differentiating ten different intensity levels, the scale ranges from “no research activity”, indicated by the dark blue color, to “highly intensive research activity”, indicated by the yellow color.

Overview of Key Findings

All in all, numerous overarching conclusions emerge from our analysis of the AM research landscape, as described in the following.

The research focus is on PBF Plastic and Metal technology.

The analysis of research landscape has shown that the research focus is on PBF Plastic and PBF Metal Technologies. Six of the considered institutes are specialized on these technologies, including the profound research activity at the University of Erlangen Nuremberg. Only a few institutes deal with FLM and Polymerization technologies, e.g. at the Nottingham University or University of Texas at El Paso.

Design rules is one cross-technological research field.

The research field *design rules* is one cross-technological research field, meaning that investigations typically involve more than one technology. Most institutes focus technology across a number of research fields. Altogether, the research intensity is balanced in most research fields, which is reflected in the fact that the overall research intensity correlates with number of institutes (the more institutes, the higher the intensity).

Research on mechanical properties for PBF Technologies is outstanding.

The analysis also revealed the research fields with the highest and lowest research intensity, see figure 2-31. An outstanding intensity is prevalent in research in *mechanical properties* for PBF Plastic and PBF Metal Technologies. This also applies to *new materials* and *material quality*. More than two third of the considered institutes are investigating in these research fields. Research fields with a rather low research intensity are especially *supply chain optimization*, *machine costs* and *process automatization*. Just a few institutes are investigating in these fields, if any at all with a moderate/negligible intensity.

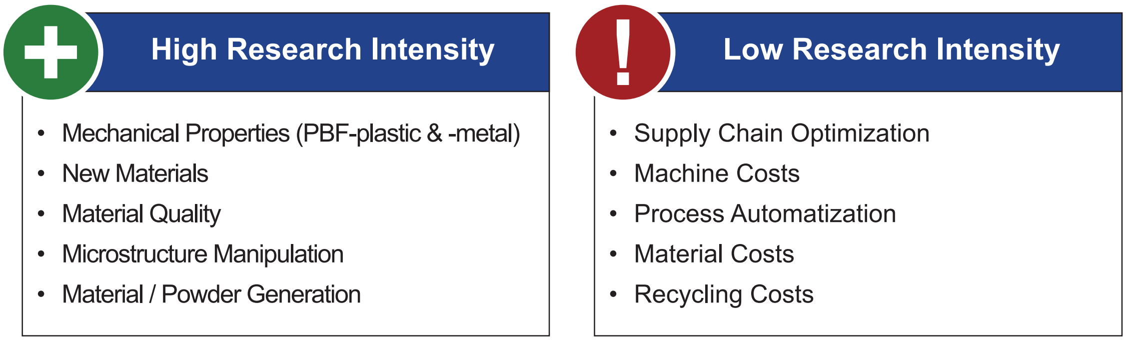


Figure 2-31: Overview on research fields with the highest and lowest research intensity in the AM Research Map

Widely represented (addressed by many institutes), but low intensity research fields are for instance *part tolerances* and the development of *standards for testing procedures*. In contrast, *temperature resistance*, *material or powder generating processes* and *simulation of parts and materials* are research fields where a few institutes are highly active in.

Material research is the most intense research field.

Comparing the research activity across the six categories, it can be stated that **material research** does represent the most intense research field: on the one hand, the majority of institutes is working in this area; on the other hand, the research intensity is comparably higher than in other research fields. Especially noteworthy is the research intensity of the Collaborative Research Center 814.

The research fields within **product research** are allocated quite heterogeneously among the institutes. Some institutes focus on a few fields across many technologies (e.g. iLas & LZN, Sheffield, NIST); others cover all fields for one technology (e.g. IFAM). Increased research occurs in the field of *light-weight structures*, *part tolerances and design rules*. *Lattice structures* count medium research activity.

For process research, a quite low research activity is indicated.

The category **process research** yields a low research activity. For PBF Plastic Technologies, the Collaborative Research Center 814 and the University of Sheffield cover many research fields with a quite high intensity. Regarding PBF Metal Technologies, the University of Sheffield and the KU Leuven indicate a high research intensity.

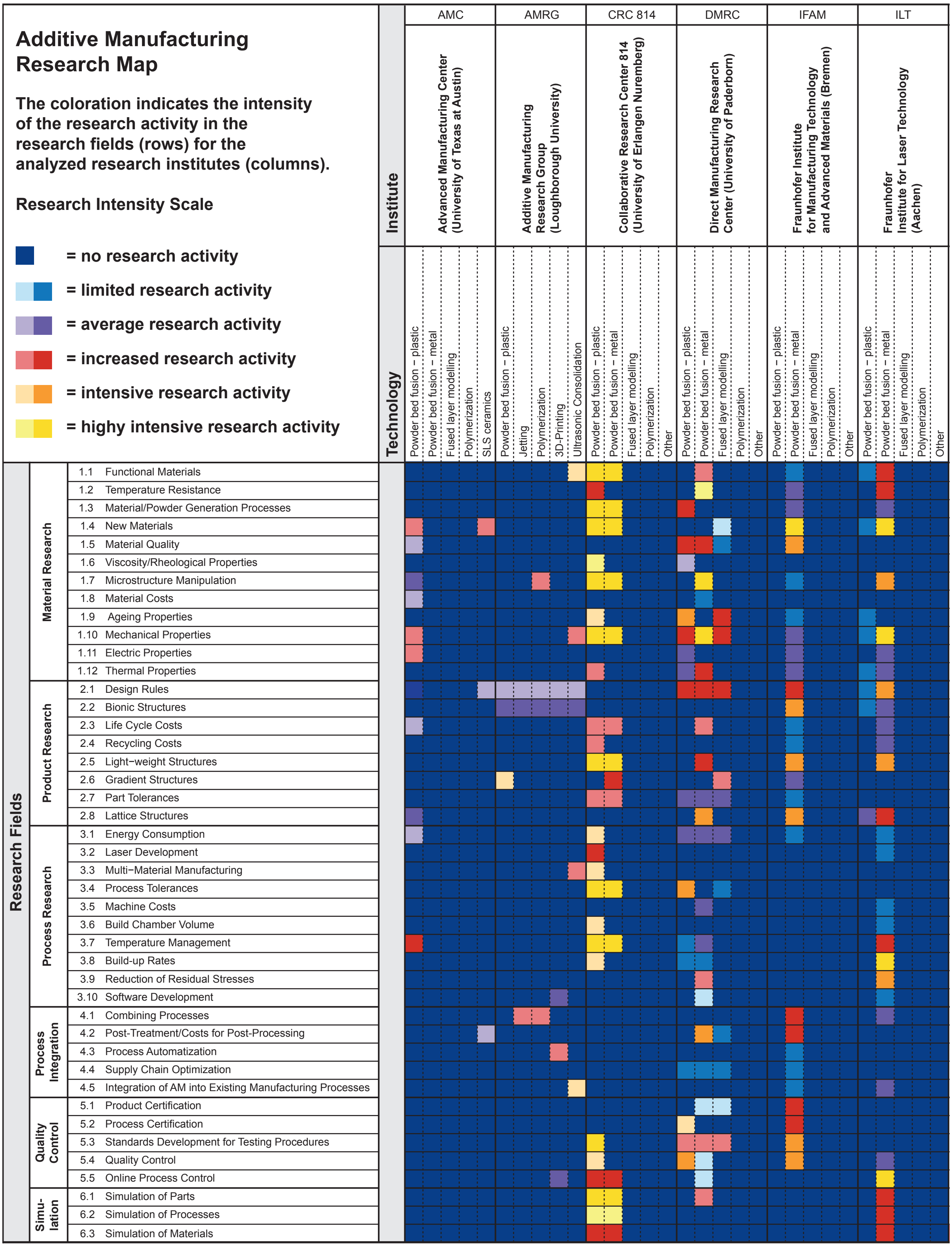


Figure 2-32: Additive Manufacturing Research Map (1/2)

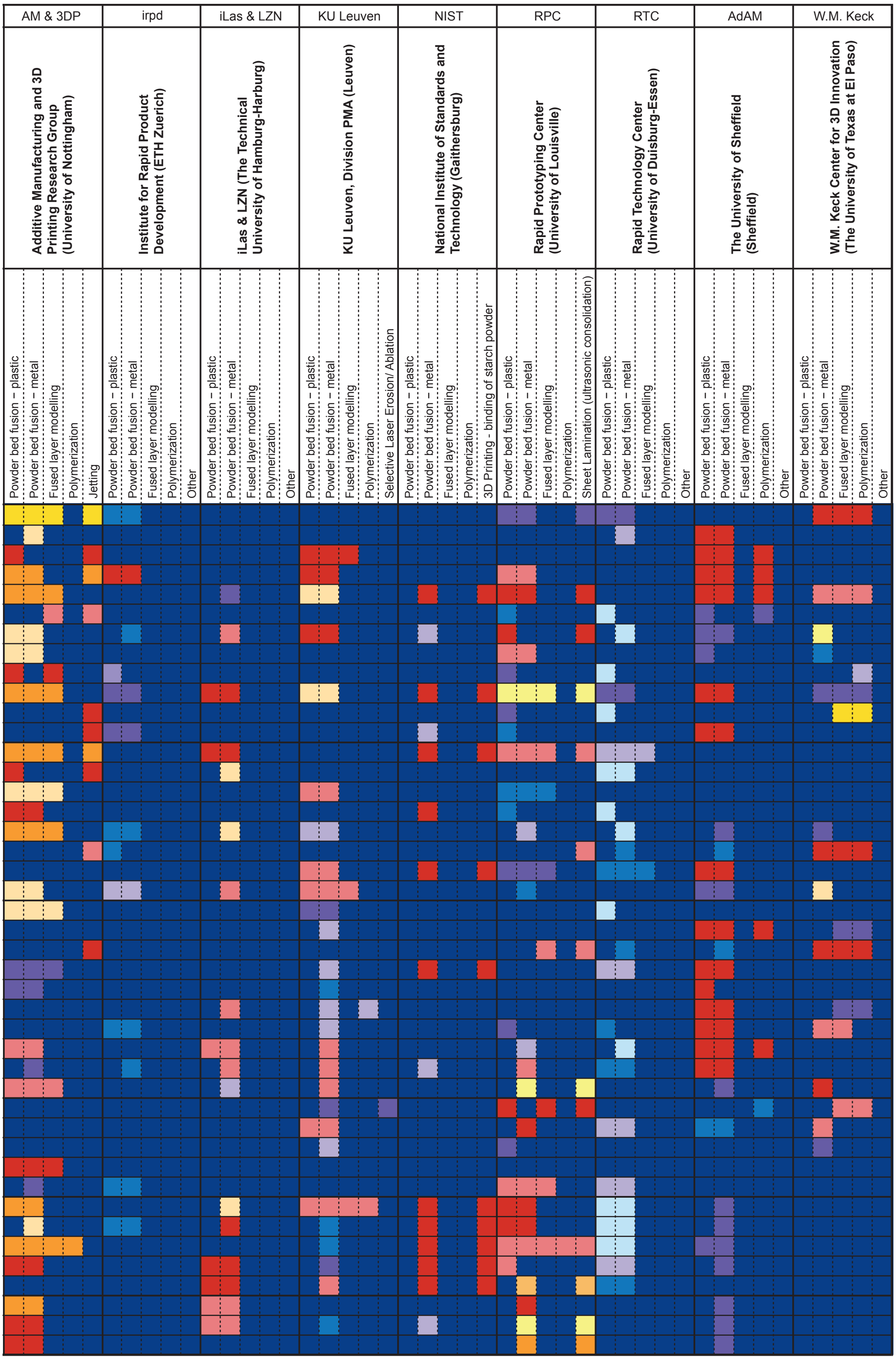


Figure 2-33: Additive Manufacturing Research Map (2/2)

The research activity in process integration is comparably low.

The research activity in **process integration** is as low as for process research. The IFAM has a medium research activity in combining processes and exploring post-treatments processes for PBF Metal Technologies. The Rapid Prototyping Center in Louisville indicate a medium research activity across many research fields, especially underlining the integration of AM; the addressed technologies are: PBF Metal and FLM Technologies, Sheet Lamination – Ultrasonic Consolidation.

Quality control has a medium research activity.

Quality control involves a medium research activity. The Rapid Prototyping Center in Louisville strikes with a high research activity across all research fields. IFAM and NIST pursue research across all research fields for PBF Metal Technologies. NIST additionally focuses 3D-Printing – binding of starch powder. KU Leuven examines quality control issues for SLM technology.

Simulation of AM is represented with a relatively low intensity.

The category **simulation** is represented with a relatively low intensity. The Collaborative Research Center 814 has high activity across all fields for PBF Metal und PBF Plastic Technologies, especially focusing the simulation of parts. The Rapid Prototyping Center in Louisville has outstanding research activity in simulation of processes and materials in PBF Metal Technologies and Sheet Lamination.

2.4.1 Evaluation of the Institute-Specific Research Intensity

The characteristics presented in chapter 2.1 comprise radar charts, indicating the institute's activity aggregated for the six defined categories: materials research, product research, process research, process integration, quality control and simulation, see figures 2-2 to 2-16. The diameter of the bubbles in these charts indicates how many research fields the respective institute addresses in its research work. A small diameter indicates that research is done in two research fields at maximum, the medium one specifies a research activity at most in nine research fields, and the large one points to a research activity in at least ten research fields. This data directly derives from the AM Research Map. The following sections briefly summarizes the key findings for each institute.

Advanced Manufacturing Center (University of Texas at Austin)

The Advanced Manufacturing Center, University of Texas at Austin, indicated to be active in selected research fields for PBF Plastic and SLS Ceramics Technologies. Material research and process research represent the main research fields; no activity is attributed to quality control and simulation.

Additive Manufacturing Research Group (Loughborough University)

The research activities at the Additive Manufacturing Research Group at Loughborough University are distributed among five AM-technologies: PBF Plastic, Jetting, Polymerization, 3D-Printing and Ultrasonic Consolidation. The institute concentrates on a few research field in all categories, except simulation. The focus is on process integration and material research.

Collaborative Research Center 814 (University of Erlangen-Nuremberg)

The Collaborative Research Center 814 in Erlangen-Nuremberg is involved in almost all research fields for PBF Metal and PBF Plastic Technologies; in the field of process integration, no research research activity is indicated. All other research fields are treated with high intensity. Especially noteworthy is the highly intensive research activity in the field of simulation.

Direct Manufacturing Research Center (University of Paderborn)

The research profile of the DMRC is quite equally distributed over all research fields with medium research intensity on average. In the field material research and product research, the research activity is above average. Low-intense research is done in the fields of process integration. As one of the few institutes, the DMRC is investigation on FDM (Fused Deposition Modeling) technology.

Fraunhofer Institute for Manufacturing Technology and Advanced Materials (Bremen)

The Fraunhofer Institute for Manufacturing Technology and Advanced Materials is specialized in PBF Metal Technologies and has a strong focus on the research fields in quality control. Medium research activity is indicated in the field of material research, product research and process integration. In process research and simulation the institute specifies its research activity as relatively low.

Fraunhofer Institute for Laser Technology (Aachen)

The Fraunhofer Institute for Laser Technology deals with the AM-technologies PBF Metal and PBF Plastic. It has a comparably outstanding research activity in quality control, high research activity in material and process research, and quite intensive activity in simulation.

Additive Manufacturing and 3D Printing Research Group (The University of Nottingham)

The Additive Manufacturing and 3D Printing Research Group at the University of Nottingham has a well distributed research profile and covers a number of research fields in its research, concurrently addressing many AM-technologies (PBF Metal, PBF Plastic, FLM, Polymerization and Jetting Technologies). Outstanding strengths are material research and product research as well as quality control and simulation.

Institute for Rapid Product Development (Zürich)

The Institute for Rapid Product Development (irpd) deals with Powder bed fusion – metal and Powder bed fusion – plastic, but has a low research activity in all fields. The institute mainly concentrates on material research. The institute is not active in simulation.

Technical University Hamburg-Harburg

The Technical University Hamburg-Harburg (iLAS & LZN) concentrates on PBF Metal and PBF Plastic Technologies. Its research activity is distributed among all research fields, except process integration. Mostly, the research intensity is on a medium level; in the field of quality control the intensity is quite high.

KU Leuven (Division PMA)

The KU Leuven deals with four different kinds of AM technologies: PBF Metal, PBF Plastic, FLM and Polymerization. High research intensity is indicated for material research; simulation exhibits a low research intensity. Another intense field is attributed to process research, but just confined to PBF Technologies. The institute indicates joint work on transversal projects, and furthermore states to conduct studies for selective laser erosion.

National Institute of Standards and Technology Engineering Laboratory (Gaithersburg)

The National Institute of Standards and Technology Engineering Laboratory indicated to explore PBF Metal Technologies and 3D Printing Binding of Starch Powder. The institute has a distributed research activity. Its strength is the quality control research. The other research fields are treated with a medium effort; no research activity is indicated for the field of process integration.

Rapid Prototyping Center (University of Louisville)

The research activity of the Rapid Prototyping Center at the University of Louisville focus four technologies: PBF Metal, PBF Plastic, and Polymerization Technologies as well as Sheet Lamination (Ultrasonic Consolidation). The institute specifies a high research activity in all research fields, specifically in material research and quality control. Furthermore, the know-how in simulation is one of the best among the institutes considered in the AM Research Map.

Rapid Technology Center (University of Duisburg-Essen)

The Rapid Technology Center (RTC) in Duisburg-Essen is involved in research on PBF Metal, PBF Plastic and FLM Technologies. Its research activity is distributed among all research fields, but the research intensity is low. The focus is on process integration. The RTC indicates joint research on transversal projects in design rules and part tolerances.

The University of Sheffield (Department of Mechanical Engineering)

At the Department of Mechanical Engineering in Sheffield the AM-technologies PBF Metal, PBF Plastic and Polymerization Technologies are focused. Process research is the institute’s strongest field followed by material research. Lower research activity is stated for process integration and product research.

W.M. Keck Center for 3D Innovation (The University of Texas at El Paso)

The W.M. Keck Center at the University of Texas at El Paso has a unique combination of the applied technologies in the analyzed AM research landscape. It deals with PBF Metal, FLM and Polymerization Technologies. The research activity is closely related to certain research fields, e.g. electric properties, microstructure manipulation or lattice structures. No research activity is indicated in the field of quality control or simulation.

2.4.2 Evaluation of the Technology-Specific Research Intensity

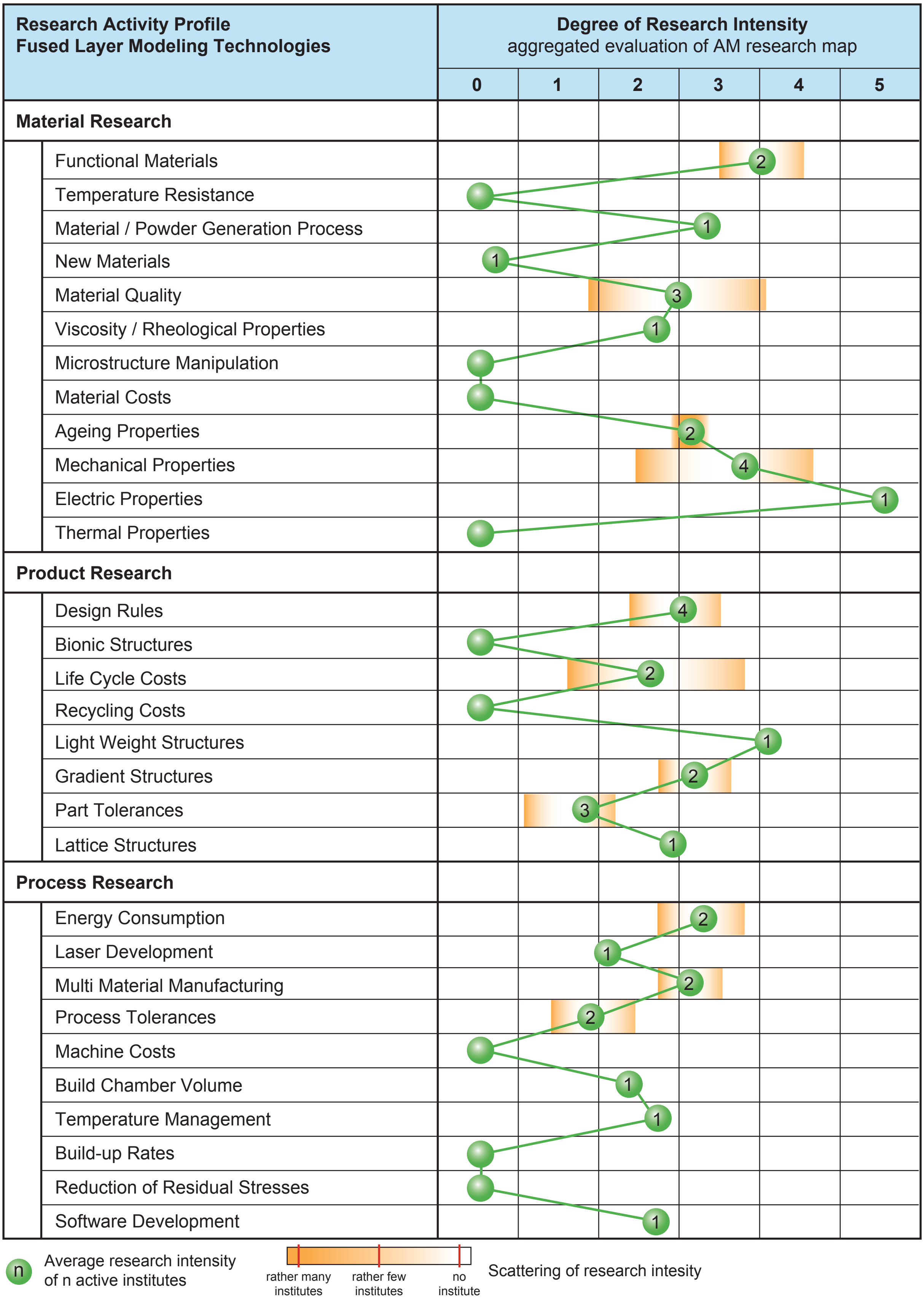
In this chapter, technology-specific research intensity profiles deduced from the AM Research Map are presented. The stimulus for this analysis derives from the question, how the research activity is distributed if the institutes' research activity is aggregated for each considered technology? Thus, cross-institute findings for any technology can be made. From the aggregated research activity profiles, both the average research intensity for each technology as well as the scattering of intensity can be derived. In these profiles, the position of the bubble indicates the research intensity for a kind of "virtual institute"; the number indicates the number of institutes dealing with this research-field-technology-combination. The orange bars indicate the scattering of the research intensity, for instance from a low to a high intensity; the depth of the color gives hints on the relative number of institutes working with the respective intensity. For instance, an average medium intensity does prevail either if two institutes indicated a medium intensity or of respectively one institute indicated a low and a high intensity.

2.4.2.1 Fused Layer Modeling Technologies

The research activity in FLM-technologies is low.

The technology-specific research intensity profile for FLM-technologies is shown in figure 2-34. At a first glance, the overall result shows that the research activity is low for FLM-technologies:

- Just a few institutes indicated to conduct research for this technology with a low research intensity: four institutes are active at maximum: Direct Manufacturing Research Center (Paderborn), Additive Manufacturing and 3D Printing Research Group (Nottingham), Rapid Prototyping Center (Louisville), and W.M. Keck Center for 3D Innovation (Texas).
- However, approximately one third of all research fields are not addressed at all; on average, just one institute is addressing just one research field.
- In **material research**, a highly intensive research work is done by the W.M. Keck Center for 3D Innovation (Texas) in the field of electric properties. Other material related topics that are treated with an increased activity are functional materials, mechanical properties and material quality.


Research Activity Profile
Fused Layer Modeling Technologies
Degree of Research Intensity
aggregated evaluation of AM research map
0
1
2
3
4
5
Material Research
Functional Materials
Temperature Resistance
Material / Powder Generation Process
New Materials
Material Quality
Viscosity / Rheological Properties
Microstructure Manipulation
Material Costs
Ageing Properties
Mechanical Properties
Electric Properties
Thermal Properties
Product Research
Design Rules
Bionic Structures
Life Cycle Costs
Recycling Costs
Light Weight Structures
Gradient Structures
Part Tolerances
Lattice Structures
Process Research
Energy Consumption
Laser Development
Multi Material Manufacturing
Process Tolerances
Machine Costs
Build Chamber Volume
Temperature Management
Build-up Rates
Reduction of Residual Stresses
Software Development
n
Average research intensity of n active institutes
rather many institutes
rather few institutes
no institute
Scattering of research intesity

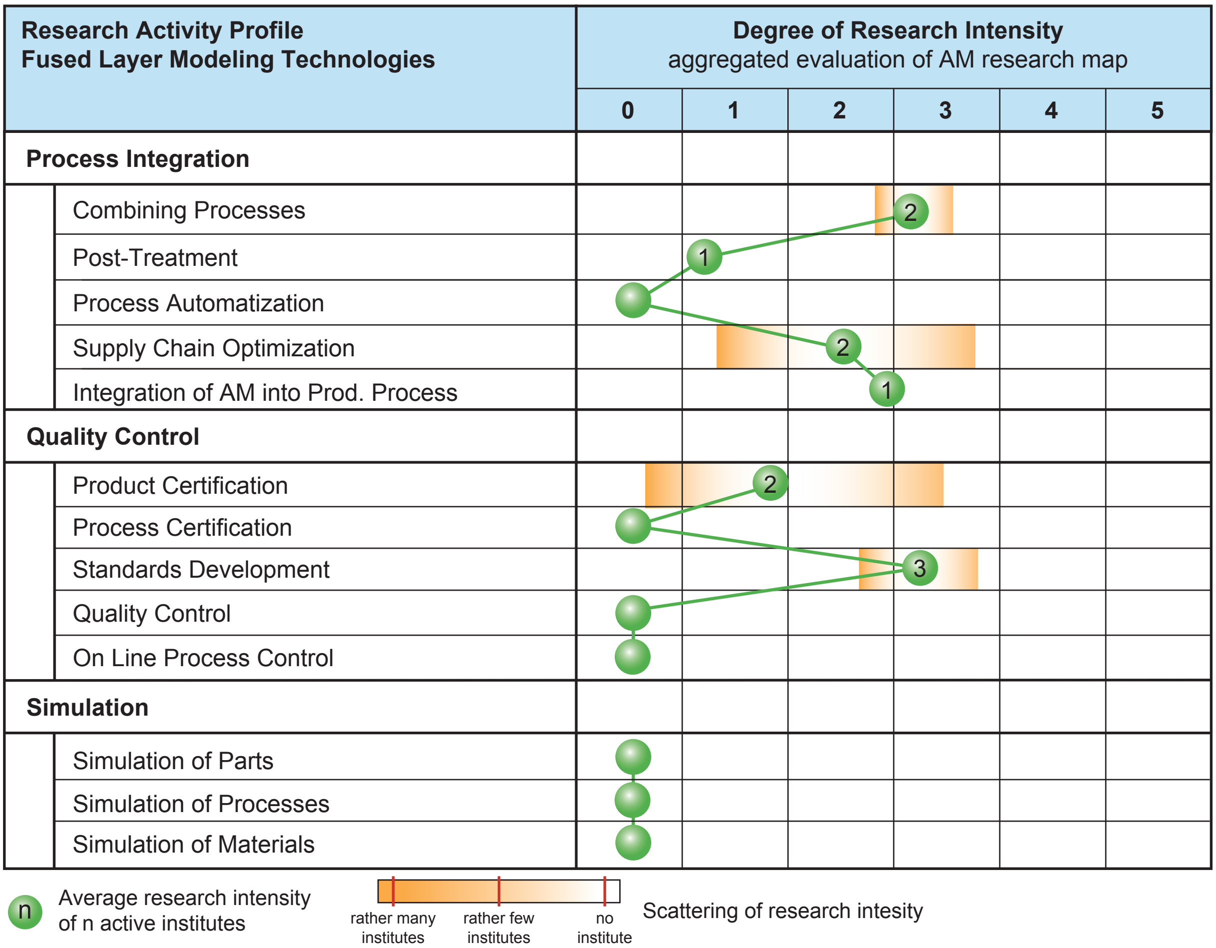


Figure 2-34: Technology-specific research intensity profile for Fused Layer Modeling Technologies

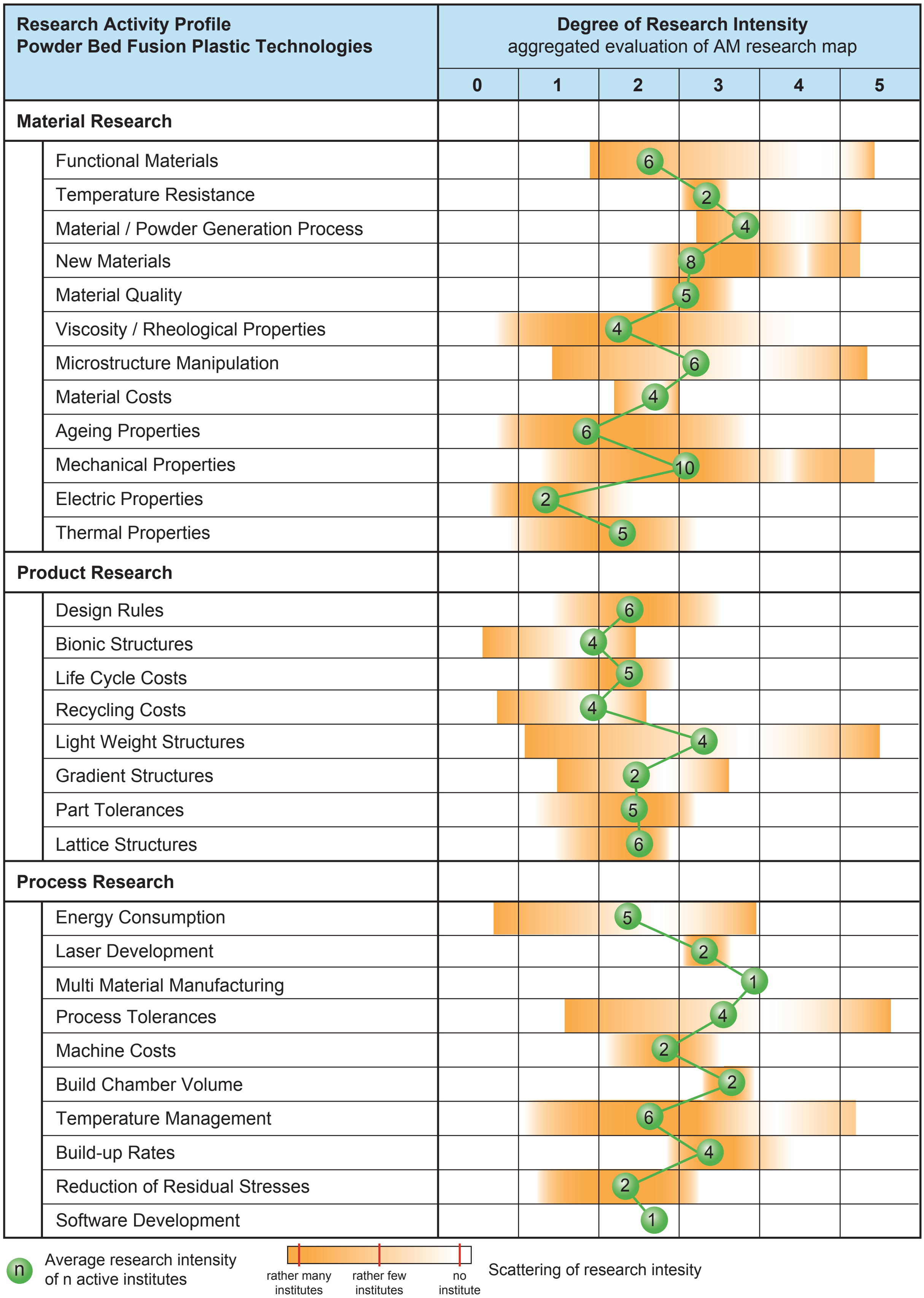
- **Product research** with at least increased intensity is conducted for design rules, gradient structures and light weight structures. Bionic structures and recycling costs are not addressed. Design rules is a field which is explored by four institutes in the analyzed research landscape.
- For **process research**, the research fields multi material manufacturing and energy consumption are represented with medium activity by two institutes. There is no activity indicated for fields like machine costs and build-up rates.
- Equal conclusions emerge for the process automatization in the category **process integration**. Here, combining processes and supply chain optimization is treated the most.
- Especially the category **quality control** is barely considered within the analyzed research landscape. Addressed research fields are standards development and product certification.
- In the category **simulation**, no research activity is indicated.

2.4.2.2 Powder Bed Fusion Plastic Technologies

The research activity in PBF Plastic Technologies is relatively high.

The research activity for PBF Plastic Technologies is quite high. On average, four institutes are working on one research field, and all research fields are explored by at least one institute. Figure 2-35 shows the technology-specific profile for PBF Plastic Technologies.

- The most common research field is **material research**, especially the research fields mechanical properties, new materials and microstructure manipulation. Investigations on material/ powder generation process count the highest research activity: three institutes are involved therein.
- **Product research** is also widely explored by the institutes, but the average research intensity is rather low. The deepest know-how prevails in the field of light weight structures; especially noteworthy is the research activity of the CRC 814 (Erlangen-Nuremberg) and the Additive Manufacturing and 3D Printing Research Group (Nottingham).
- **Process research** is addressed by several institutes with a medium intensity. Research within process certification is indicated as low.
- For PBF Plastic Technologies, the lowest research intensity is attributed to **process integration** among the analyzed institutes. Only five institutes are involved in this research category; except of the Rapid Prototyping Center (Louisville) no institute is investigating in more than one research field. Hence, the average research activity is low.
- Several institutes indicate research activity within the category **quality control** as medium.
- Just a few institutes address **simulation** for this technology; however, the research intensity these institutes indicate is quite high, especially in simulation of parts.


Research Activity Profile
Powder Bed Fusion Plastic Technologies
Degree of Research Intensity
aggregated evaluation of AM research map
0
1
2
3
4
5
Material Research
Functional Materials
Temperature Resistance
Material / Powder Generation Process
New Materials
Material Quality
Viscosity / Rheological Properties
Microstructure Manipulation
Material Costs
Ageing Properties
Mechanical Properties
Electric Properties
Thermal Properties
Product Research
Design Rules
Bionic Structures
Life Cycle Costs
Recycling Costs
Light Weight Structures
Gradient Structures
Part Tolerances
Lattice Structures
Process Research
Energy Consumption
Laser Development
Multi Material Manufacturing
Process Tolerances
Machine Costs
Build Chamber Volume
Temperature Management
Build-up Rates
Reduction of Residual Stresses
Software Development
6
2
4
8
5
4
6
4
6
10
2
5
6
4
5
4
4
2
5
6
5
2
1
4
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2
6
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2
1
n
Average research intensity
of n active institutes
rather many
institutes
rather few
institutes
no
institute
Scattering of research intesity

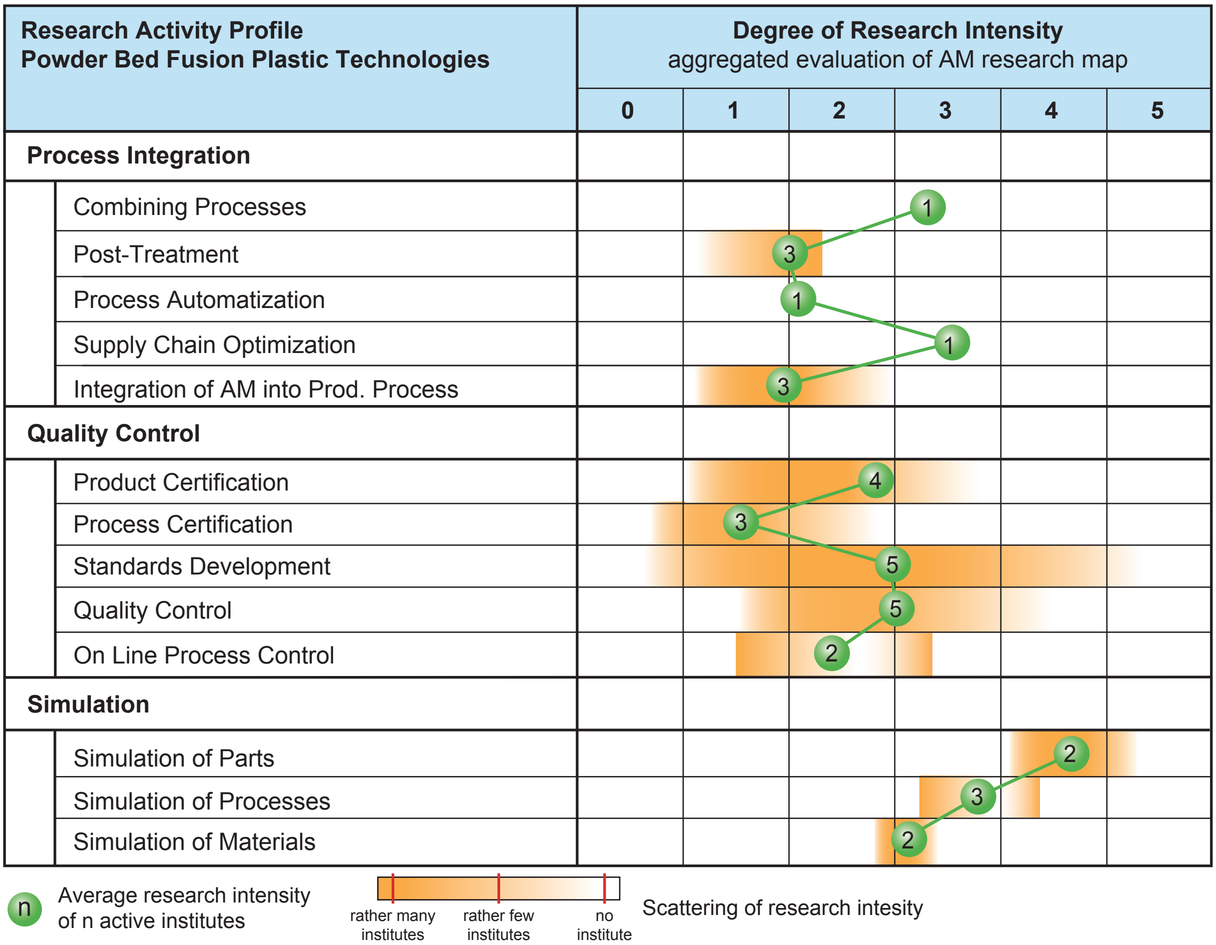

Figure 2-35: Technology-specific research intensity profile for Powder Bed Fusion Plastic Technologies

2.4.2.3 Powder Bed Fusion Metal Technologies

PBF Metal Technologies involve the highest research activity in the research landscape.

In comparison to all technologies addressed in the analysis of the AM research landscape, the highest research intensity does prevail for PBF Metal Technologies distributed over all research fields. On average, more than six institutes are involved in one research field. The technology-specific profile is shown in figure 2-36.

- The most common research fields in the category **material research** are mechanical properties and microstructure manipulation. At least two third of the considered institutes are dealing more or less intensive with these research fields. The most intense research work is done in the field of new materials.

- In ***product research***, the research field light weight structures is indicated by 11 institutes, followed by lattice structures and design rules for PBF Metal Technologies. Bionic structures and investigations in life cycle costs are also mentioned by a number of institutes; here, the distribution is not equal, meaning that a few institutes indicate a low research intensity and a few a really high intensity.


Research Activity Profile
Powder Bed Fusion Metal Technologies
Degree of Research Intensity
aggregated evaluation of AM research map
0
1
2
3
4
5
Material Research
Functional Materials
8
Temperature Resistance
5
Material / Powder Generation Process
5
New Materials
8
Material Quality
8
Viscosity / Rheological Properties
Microstructure Manipulation
11
Material Costs
3
Ageing Properties
1
Mechanical Properties
12
Electric Properties
2
Thermal Properties
5
Product Research
Design Rules
8
Bionic Structures
5
Life Cycle Costs
6
Recycling Costs
4
Light Weight Structures
11
Gradient Structures
5
Part Tolerances
7
Lattice Structures
9
Process Research
Energy Consumption
4
Laser Development
3
Multi Material Manufacturing
3
Process Tolerances
6
Machine Costs
3
Build Chamber Volume
4
Temperature Management
6
Build-up Rates
7
Reduction of Residual Stresses
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Software Development
7
n
Average research intensity of n active institutes
rather many institutes
rather few institutes
no institute
Scattering of research intesity

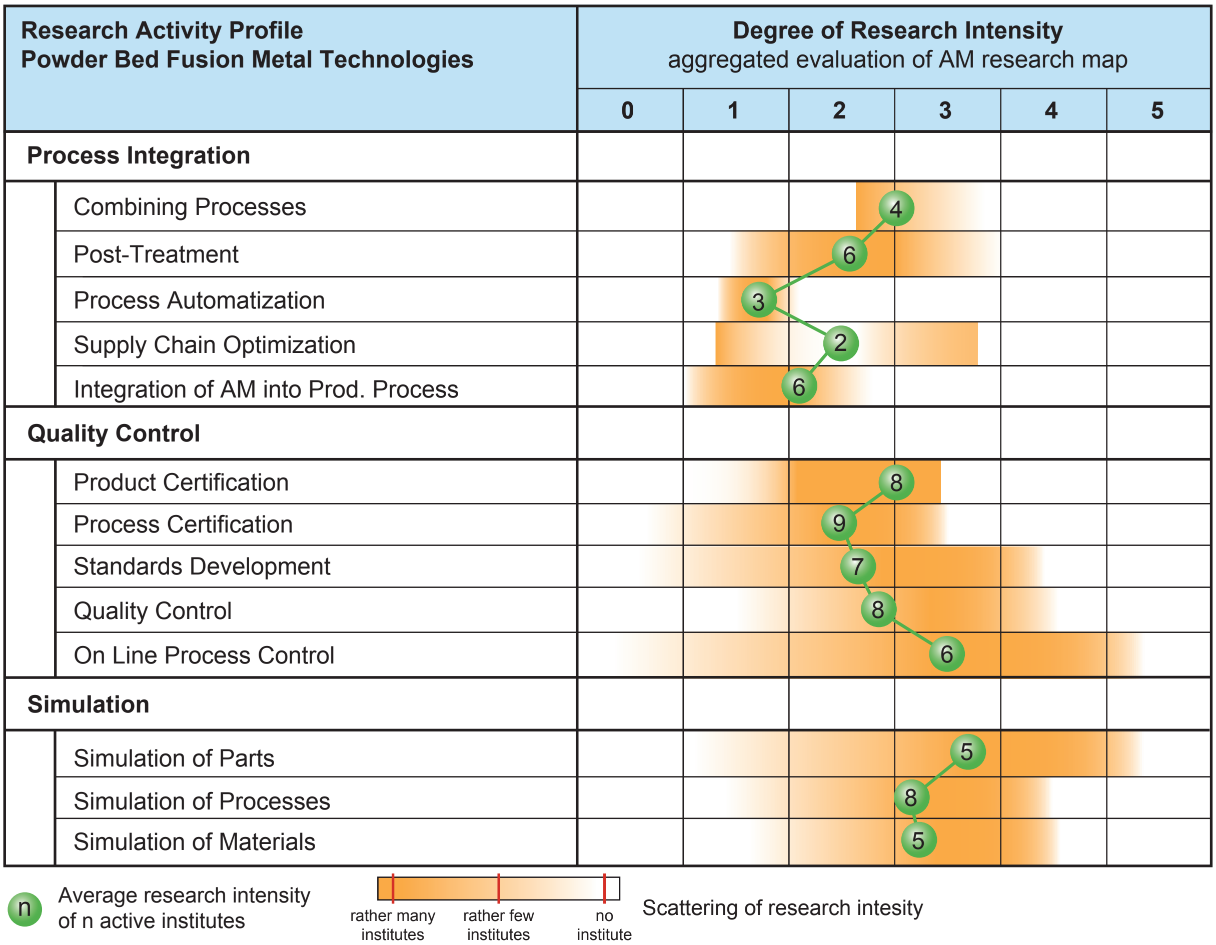


Figure 2-36: Technology-specific research intensity profile for Powder Bed Fusion Metal Technologies

- **Process research** with an at least medium research activity is conducted in all research fields; the most institutes are working on improving the build-up rates, reducing residual stresses and developing software solutions.

- Integration of PBF Metal Technologies into existing production processes and exploring post treatment methods belong to the research fields with a medium research activity in the category **process integration**, cross-technologically representing a comparatively high intensity. 6 institutes are involved therein.

- In comparison to other AM technologies, the research intensity in the categories **quality control** and **simulation** is notably high. All research fields are addressed by at least 5 institutes.

- Research fields that are scarcely investigated for PBF Metal Technologies are ageing properties, only treated by IFAM (Bremen), supply chain optimization, just addressed by IFAM and Additive Manufacturing and 3D Printing Research Group (Nottingham) and electric properties, indicated by IFAM and ILT (Aachen). Low research intensity also prevails in the research fields machine costs and process automatization.

2.4.2.4 Polymerization Technologies

For Polymerization Technologies, the lowest research activity of all technologies is indicated.

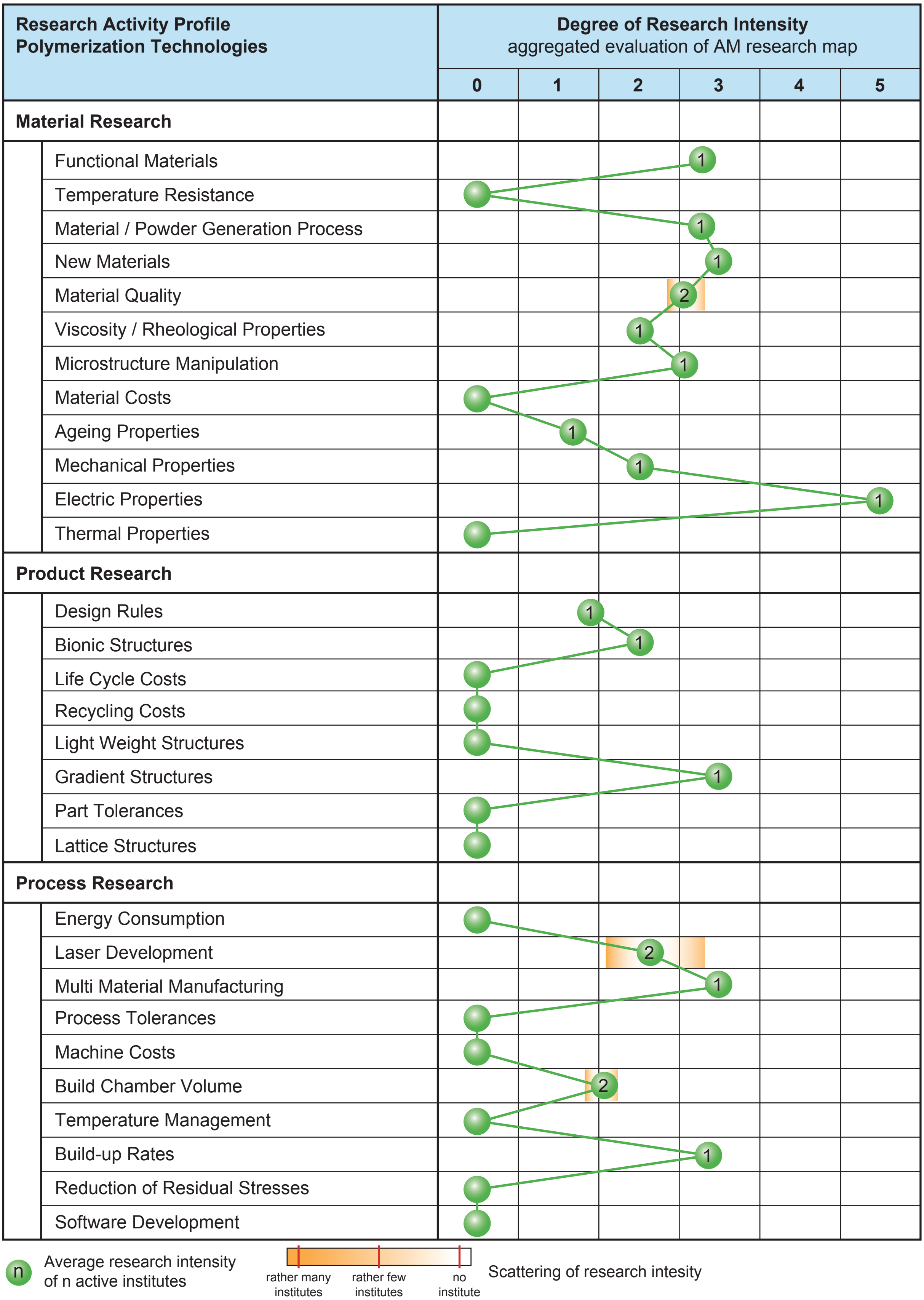
The research intensity in the field of Polymerization technologies is really low. Although six institutes are investigating Polymerization technologies, the activity is widely spread. Thus, the most research fields are focused by just one institute, as shown in figure 2-37.

- **Material research** is the most common research category for these technologies. Three of the six institutes are doing research in material research. Two institutes are doing research in the field of material quality. Especially noteworthy is the comparably high research intensity indicated by one institute in the field of electric properties.
- Due to the fact that there are just two research institutes dealing with three research fields in the **product research** category, the research activity is very low. Addressed research fields are design rules, bionic structures and gradient structures, each addressed by just one institute.
- In total, just three institutes from the analyzed research landscape are involved in **process research** for Polymerization technologies. Research activity is indicated for the following research fields: laser development, multi material manufacturing, build chamber volume and build-up rates.
- In **process integration**, three institutes are dealing with just one field. All institutes are focusing on combining processes.
- For **quality control**, the research fields product certification and standards development are represented with a medium research activity. There are two institutes working on the standards development and one on product certification.
- No institute is involved in research on **simulation**.

2.5 Summary

To get a comprehensive overview on the research activity in the field of AM, an AM Research Map have been created. As part of a survey, the research activity and intensity of selected AM-institutes in the identified research fields were determined. Thus, the Research Map reveals which research fields are being intensively investigated and which are hardly examined. For instance, just a few institutes focus on cross-technological research fields, e.g. the development of design rules and standards; the research intensity is medium. Other research fields, e.g. material research, are intensively investigated. Thereby, the research landscape reveals the strengths and weaknesses of the analyzed research institutes, showing up research fields that are hardly addressed in the research landscape.

Concurrently conclusions emerge for technology-specific research intensity, differentiating four categories of technologies. For FLM Technologies, the research activity is low: just a few institutes are investigating in a few research fields, like *material quality* or *mechanical properties*.


Research Activity Profile
Polymerization Technologies
Degree of Research Intensity
aggregated evaluation of AM research map
0
1
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3
4
5
Material Research
Functional Materials
Temperature Resistance
Material / Powder Generation Process
New Materials
Material Quality
Viscosity / Rheological Properties
Microstructure Manipulation
Material Costs
Ageing Properties
Mechanical Properties
Electric Properties
Thermal Properties
Product Research
Design Rules
Bionic Structures
Life Cycle Costs
Recycling Costs
Light Weight Structures
Gradient Structures
Part Tolerances
Lattice Structures
Process Research
Energy Consumption
Laser Development
Multi Material Manufacturing
Process Tolerances
Machine Costs
Build Chamber Volume
Temperature Management
Build-up Rates
Reduction of Residual Stresses
Software Development
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Average research intensity
of n active institutes
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institutes
rather few
institutes
no
institute
Scattering of research intesity

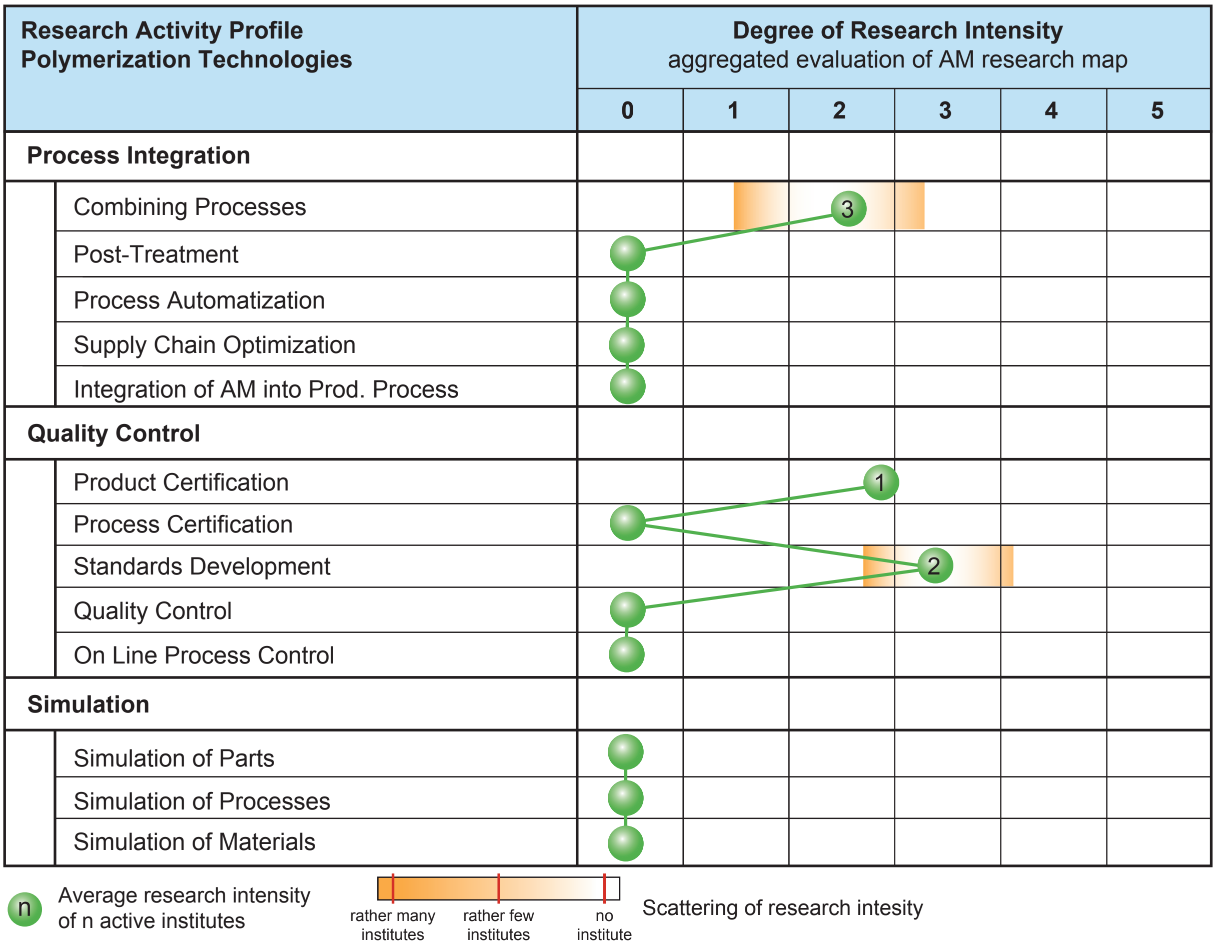

Figure 2-37: Technology-specific research intensity profile for Polymerization Technologies

In PBF Plastic Technologies, the research activity is rather high: on average four institutes are working in one research field, e.g. in the research fields *new materials* and *mechanical properties*. For PBF Metal Technologies, the institutes indicate the highest research activity in total, distributed over all research fields. On average, more than six institutes are involved in one research field. For Polymerization Technologies the lowest research activity of all technologies prevails. Especially noteworthy is the comparably high research intensity indicated by one institute in the field of electric properties.

3

Development of Research Strategies

In the previous chapter, the Additive Manufacturing research landscape was analyzed. Based on this, research fields involving a high research activity and those that are barely developed were revealed for each of the considered technologies separately. Well, how can these results be leveraged for developing research strategies? The answer for this question will be provided in this chapter, however, just addressing an excerpt of the results gained in the project.

Developing (research) strategies is not trivial. Typically, organizations, e.g. research institutes or companies are confronted with a high amount of information. Decision makers frequently have to cope with great challenges while deducing a strategic direction out of this information, concurrently considering time pressure and the competitors' behavior. Due to this, decision makers are often satisfied if one plausible strategy variant results. In contrast to this, the quality of strategy development increases if more than one strategy variant can be found for being taken into account [FE96].

At the Heinz Nixdorf Institute, we usually follow the VITOSTRA® method which helps identifying consistent strategy variants. Each strategy variant contains a set of different strategic variables, representing strategic levers a company/institution can adjust to different positions [GPW09]. In the context of research strategies, it is important to not solely concentrate on technological levers – conceivable technological positions; additionally, it is important to take resulting mandatory organizational levers into account.

To identify crucial levers for future strategies, the research fields that are of importance in the future and are barely developed at the same time – so called *white spots* need to be revealed. Therefore both, activity and intensity of today's research have to be contrasted with the future relevance of the research fields. To determine the future relevance, the Heinz Nixdorf Institute and the DMRC conducted an expert survey. Chapter 3.1 provides an excerpt of these results. In chapter 3.2, the method VITOSTRA® is briefly presented. Chapter 3.3 describes how all generated results were merged to develop consistent research strategies. This includes examples for strategic variables with possible characteristics, the developed consistent research strategies and a comparison with the strategies of the analyzed institutes.

An expert survey on future relevance of AM research was conducted.

3.1 Future Relevance of Additive Manufacturing Research

This chapter presents the results of the expert survey on Future Relevance of Research Fields for the Additive Manufacturing Industry that was conducted to reveal the most important research fields, in terms of future relevance for the industrial penetration of AM-technologies. These results are used to develop future-oriented research strategies.

Structure of the Survey

Wide ranging expertise of participants

The survey was conducted in English in the period from February until June 2013. To reflect the opinion of the entire AM-industry, the survey addresses AM-experts along the whole value chain: AM-machine manufacturers and material suppliers, users of AM-technologies (OEMs and suppliers) as well as universities and research facilities dealing with AM-technologies. The survey was sent to **385 AM-experts**; **107 contacts (28%) completed the survey**.

The survey is divided into three parts: *General Information*, *Future Relevance of Research Fields for the Additive Manufacturing Industry/Time of Relevance* and *Final Statements*. The first part addresses the professional background of the experts. In the second part, the experts were asked to assess each research field regarding its future relevance for the AM-industry; moreover, the experts were asked to indicate the time when – from the experts' point of view – research in the listed fields might become relevant. The final part outlines final statements of the experts. This chapter provides an excerpt of the results; detailed results are part of the confidential study which is accessible for DMRC partners only.

General Information

The majority of the participants are technology experts.

This chapter presents the professional background of the experts. First, the experts were asked to indicate their field of activity. 97% of all participants indicate to have expertise in the field of technology and 33% in market and competition. Secondly, the experts specified the part of the value chain of AM and the company division they are working in. The percentage distributions are shown in the following two bar charts (note: multiple choices possible), see figure 3-1 and 3-2.

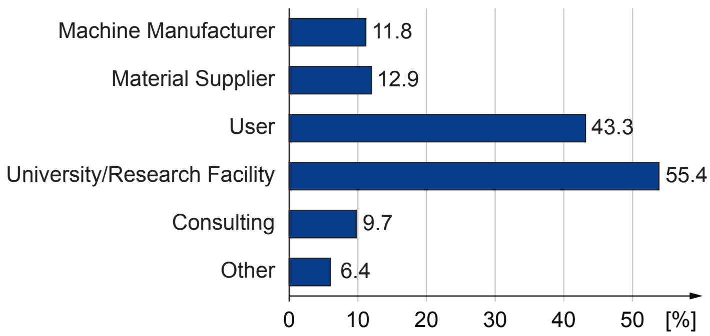

Figure 3-1: Part of the value chain the participants are working in (in percentage terms)

With a share of 55% and 43%, research facilities and users count the largest share among all participants, followed by, material suppliers, machine manufacturers and consulting, see figure 3-1. The *Other* category includes participants that do not fit into the listed categories.

Figure 3-2 illustrates the heterogeneous composition of the participants, as the range covers all company divisions, except of the division purchase. The majority of the participants (75%) specify to work in research and development. With 20%, the management division also comprises a large proportion.

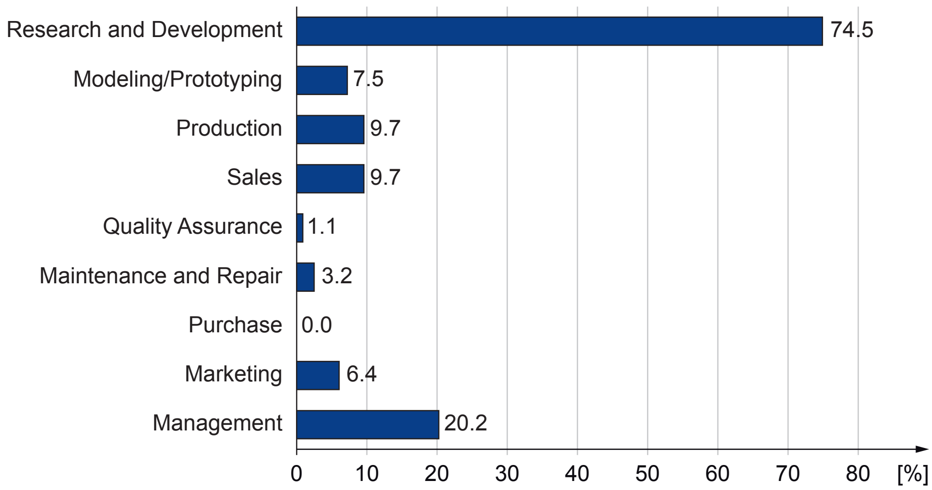

Figure 3-2: Company divisions the participants are working in (in percentage terms)

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

The bar chart in figure 3-3 illustrates in percentage terms how the participants use AM (note: multiple choices possible). 79% of the participants indicate to use AM for Direct Manufacturing and 66% for Rapid Prototyping. A third of the participants use AM for Rapid Tooling. This also correlates with the fact that the majority of the participants indicate to work in research and development divisions (see figure 2-xy).

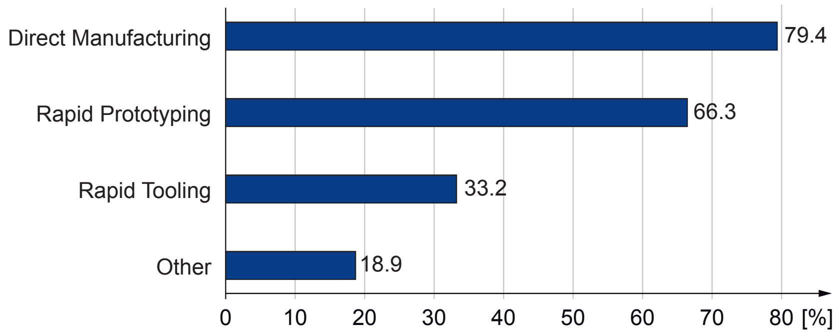

Figure 3-3: Usage of AM-technologies (in percentage terms)

3.1.1 Evaluation of the Future Relevance and the Time of Relevance

This chapter outlines the experts' assessment of the future relevance of AM research. Therefore, the same 43 research fields were addressed as used in the analysis of the AM research landscape. For a detailed description of the research fields, see chapter 2.2.

In a first step, the experts were asked to specify the relevance of each research field for the industrial penetration of AM, using a scale from "0" to "4" (no relevance up to high future relevance). The goal of this assessment is the identification of those research fields which will be crucial for the business of tomorrow. Based on the assessment in the survey, the arithmetic mean was determined for both the future relevance of the research fields. In a second step, the experts were asked to estimate the time of relevance for the listed research fields, ranging from "now" over "2015" to "2025". Among all participants, the arithmetic mean for the time of relevance was determined for each considered research field.

Consolidating the results for the future relevance and the time of relevance that has been determined, the need for action for further development and optimization in specific research fields of the technology can be deduced. On the basis on the data collected, each research field is positioned in a Future-Relevance/Time-of-Relevance portfolio, as visualized in the following figures. In these portfolios, the ordinate intercept shows the future relevance of the research fields; the abscissa intercept indicates when a research field is expected to become relevant in the future.

In the following, exemplarily excerpts of the results are provided: the portfolio for the category *material research* and *product research*. Comprehensive results are part of the confidential study. In these portfolios, we suggest to distinguish five areas, as shown in figure 3-4 and figure 3-5:

- "Hot Iron" – red area: These research fields are of high relevance for the business of tomorrow; the relevance is immediate. "Hot Iron" have a high research priority and indicate an immediate need for action.
- "Future Stars" – orange area: The relevance of these research fields is high, but in a mid-term time horizon. Future stars are of high priority and require a mid-term planning.
- "Rough Diamonds" – yellow area: These research fields have a high significance and are estimated to become relevant in the long-term time horizon. They have a mid-priority and require a long-term planning.
- "Observable Checkmarks" – green area: These research fields have a low significance and are expected to become relevant in the mid or long-term time frame. The priority is medium or rather low; it is crucial to monitor these research fields regarding indicators for increasing relevance.

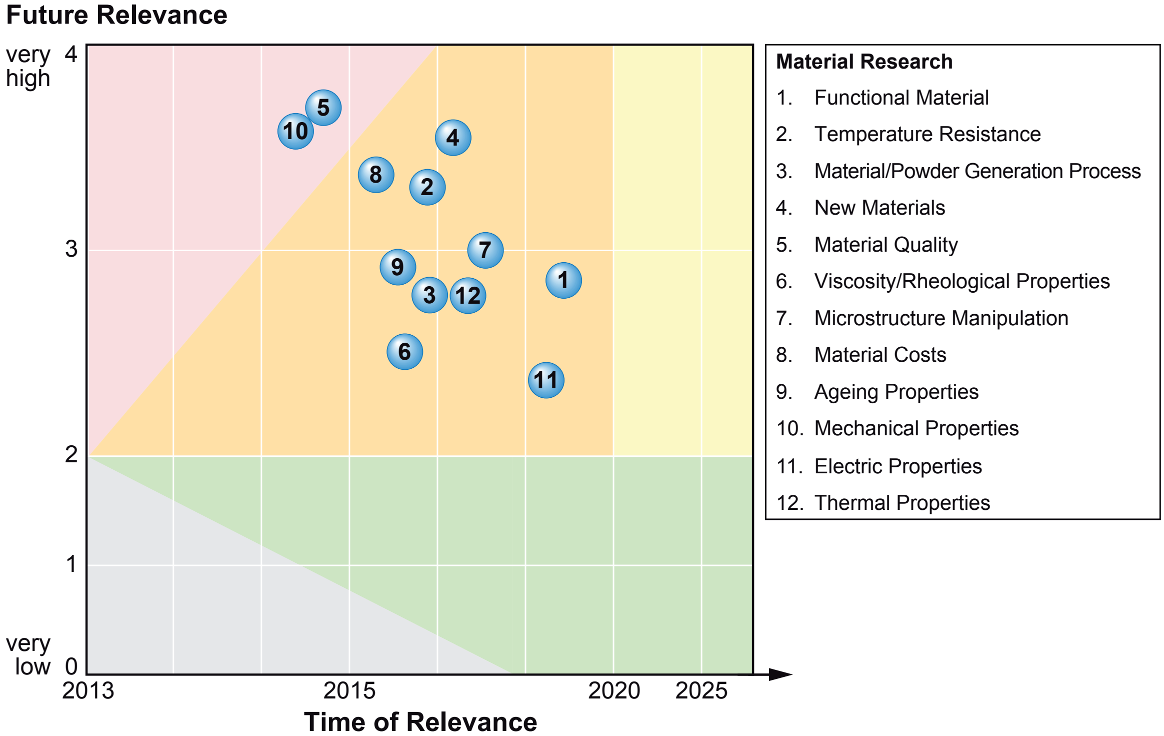

Figure 3-4: Extract from future relevance/time of relevance portfolio for material research

- "Lame Ducks" – grey area: Lame ducks have an immediate time of relevance, but its significance is low. The priority of these research fields is low and it should be decided act opportunistically whether to investigate or to neglect them.

The overall relevance of the research fields is high.

At a first glance, we can state that according to this survey no research field is of low relevance for the future penetration of AM-technologies.

Material quality and mechanical properties are of high relevance for the future.

In the category **material research**, especially the research fields *material quality* and *mechanical properties* are hot irons, meaning that these are of high and immediate relevance. All other research fields are in the orange area - highly relevant to be considered in the mid-term research, see figure 3-4. The research fields with the lowest relevance are investigations of *electric properties* and *viscosity/rheological properties*.

Design Rules and Part Tolerances are the research fields with the highest relevance.

The overall assessment for the category *product research* shows similar results as for *material research*, see figure 3-5. The research fields with the highest relevance are the development of *design rules* and research on improvement of *part tolerances*. *Recycling cost* and *bionic structures* indicate the lowest relevance in this category.

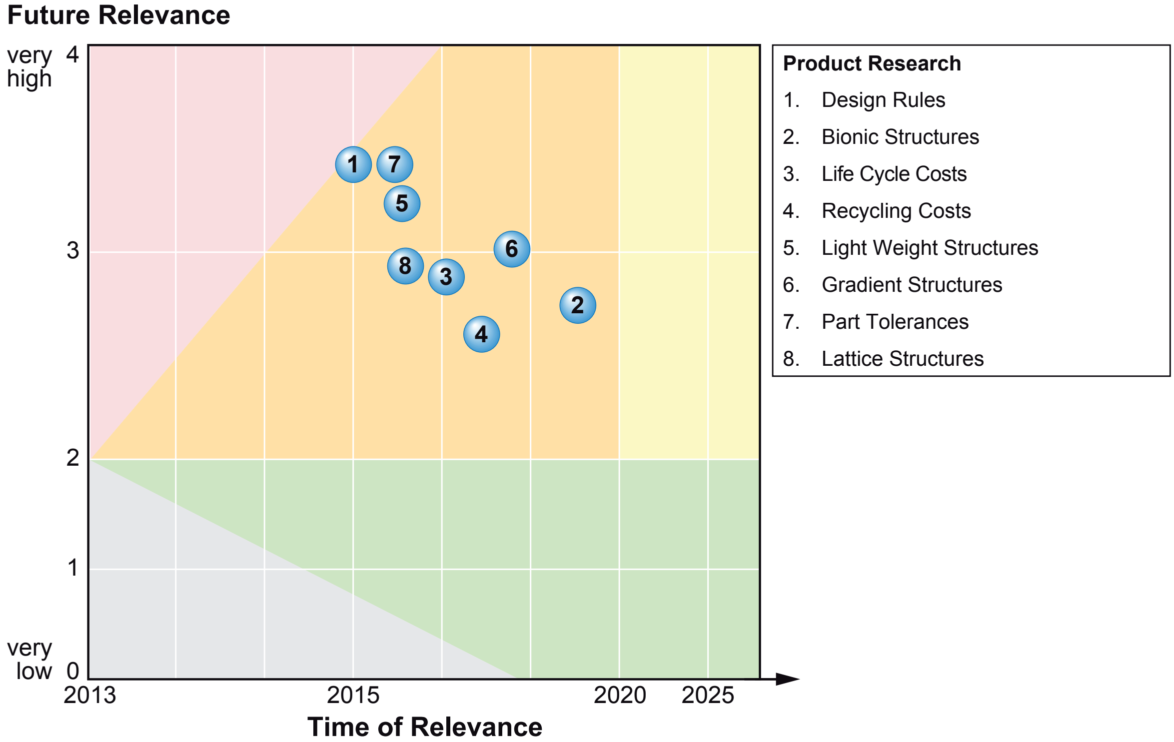

Figure 3-5: Extract from future relevance/time of relevance portfolio for product research

3.1.2 Deduction of White Spots and Success Factors for Research Strategies

By contrasting the relevance, research intensity and the technologies' performance, white spots were identified.

Instead of prematurely committing to the highly relevant research fields, it is however important to take into account the technologies' performance (derived from surveys in the preceding project) and the already prevailing research intensity in the respective research fields. Using these two criteria additionally, the research fields are positioned in a relevance-performance portfolio, as shown in figure 3-6. In this portfolio, the ordinate intercept shows the relevance of the research fields; the abscissa indicates the technology's degree of performance in these research fields. By additionally contrasting the relevance and the performance with the research intensity (indicated by the color of the bubbles), those research fields that are highly relevant for a broad penetration of AM, but insufficiently addressed in current research projects – so called *white spots* – are identified.

From the analysis of the identified *white spots* twofold implications for research strategies can emerge: technological and organizational implications. The technological implications – also called technological levers for research strategies – can be directly deduced from the position of the research fields in the portfolio in figure 3-6. For instance the research demand or the required R&D effort can be approximated by the horizontal distance between the research fields' position and the left delimiting line of the balanced area, concurrently taking into account the existing research intensity therein.

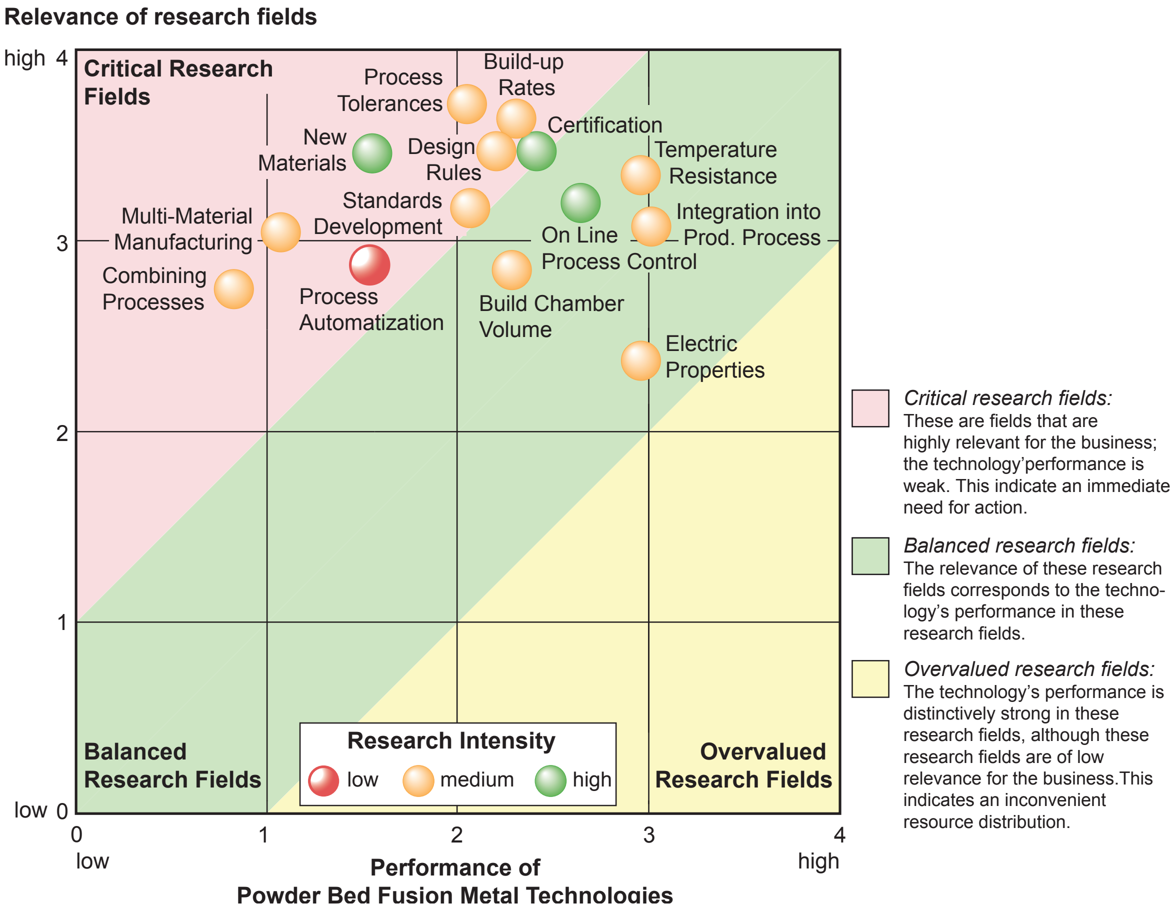

Figure 3-6: Contrasting future relevance, technology performance and research intensity for selected research fields (excerpt)

By this means, for instance the research fields *process automatization* and *design rules* were determined as technological levers that should be considered in future research strategies. Research fields, such as *new materials*, are critical for the future penetration of AM as well. Here however, the research intensity is already high.

Considering these technological levers in turn, organizational implication for research strategies emerge. For instance, especially the development of a common understanding of design rules could significantly benefit from e.g. a *stronger integration of companies along the whole value chain of AM* into the research and a *stronger interconnection of the institutes within the research landscape*. These are just a few examples how research leverage could be increased.

3.2 Developing Strategies using VITOSTRA®

VITOSTRA® is an approach for developing intelligent and consistent strategy variants.

A suitable method for the development of success promising strategies is VITOSTRA® which is shortly introduced in this chapter. Typically, a strategy is based on a large amount of activities. According to PORTER, it is not the kind of activities, but their combination which leads to a successful position in a competitive environment [Por97]. Markides summarizes that successful companies are following an unique strategy allowing them to step out of competition and play "their own game" [Mar02]. Based on this and the fact that decision makers need alternatives, we established a discursive approach for developing intelligent and consistent strategy options called VITOSTRA® [GPW09].

A strategy is based on strategic variables addressing the questions What? Who? and How?

For using VITOSTRA®, initially the business has to be precisely defined. This determines the area a company can act within. Including the competitors, the competition arena is resulting. Within a company and its competition arena or from a foresight process, strategic variables and their possible characteristics are identified. Strategic variables represent strategic levers and the alternative characteristics are the different conceivable positions for the levers the company can adjust in a strategy. Strategic variables can be found in three fields i.e. *who* (who are our customers?), *what* (what are our products and services?) and *how* (how do we provide our products and services?). Afterwards, thinkable characteristics are developed for each strategic variable. For a strategic variable *manufacturing range*, conceivable characteristics are for instance *high share of production*, *system supplier*, *land a ow share of production* [GPW09].

In the next step, combinations of characteristics matching each other are calculated using a consistency analysis. Determining the most consistent combinations and using a cluster algorithm, several consistent and therefore promising strategy variants are resulting. A strategy variant contains (at least) one characteristic from each strategic variable [GPW09].

A Strategy Map gives an overview on consistent strategy variants and competitors' strategies.

Within a branch analysis, strategies of competitors and the considered/analyzed organization (company, institute etc.) are deduced. Using multi-dimensional scaling, these results can be visualized in a Strategy Map, showing the developed strategies and the competitors' strategies arranged around them. The distance is an indicator for the contextual difference of the strategies (i.e. its characteristics); moreover, the dis-tance indicates the needed effort (in terms of time and money) for a change from one strategy to another. Assessing all strategy options concerning attractiveness and accessibility allows selecting a well-founded strategy.

3.3 Research Strategies

Once the research fields, the research intensity and the future relevance of the research fields are ascertained, research strategies are developed. A strategy can be seen as a daily guideline that guides an organization from the status quo to an imaginary situation – the aimed vision in the future. As described in chapter 3.2, a strategy is based on a number of different strategic variables which in turn may have different characteristics. Especially such characteristics need to be identified which are new and not included in the competitors' strategies.

In this chapter, an overview on strategic options considered in the project is provided, meaning strategic variables and their characteristics. Afterwards, consistent research strategies are briefly described. To create a Strategy Map for the analyzed research landscape, the research strategies the considered institutes currently pursue were analyzed. A Strategy Map gives an overview of all strategies. All results generated in the project are presented in excerpts. Detailed results are part of the confidential study which is accessible for DMRC partners only.

3.3.1 Strategic Options

16 strategic variables in three areas were used to develop ideal research strategies.

As described above, the strategic variables address three different questions that should be answered in a strategy. All in all, we identified 16 variables for the development of research strategies in AM; exemplary variables are presented in figure 3-7.

The **first question is *what*** the institute should provide its stakeholders?

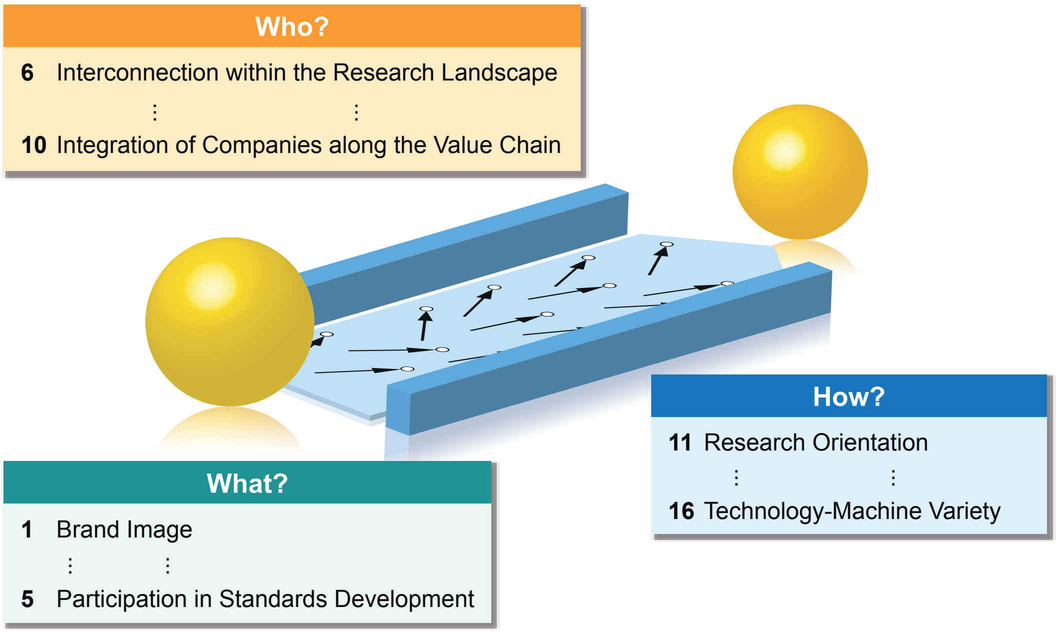

Figure 3-7: Exemplary strategic variables for designing a strategy, answering the question on What, Who and How

- In this field, five strategic variables were determined, e. g. the *brand image of the institute* and the *participation in standardization committees*. These respectively specify the institute's character, highlighting its mission and vision to (potential) customers, and the degree of involvement in the development of standards.

- Once the strategic variables are identified, conceivable characteristic are determined. Exemplary characteristics for designing a strategy are shown for three exemplary strategic variables in figure 3-8. Regarding the *brand image*, the institute may for instance pursue a strategy to be known for its outstanding expertise in *high quality education* and training for AM. Another aspired image can include outstanding research work and *scientific relevance* of its results. An institute can also strive for a reputation as an *outstanding "problem solver" and high quality service provider* in the context of AM.

The **second question is *who* are our stakeholders** and with whom do we want to cooperate or collaborate in the future? In this field, five strategic variables were determined.

- An important strategic lever for a research institute's strategy is for instance the *interconnection within the research landscape*. The interconnection of institutes describes the degree of cooperation with other (AM-)institutes. Measures for the degree of cooperation are the number of partnering institutes, collaborative research projects, joint conferences and publications as well as the extent of exchange in teaching. Some research institutes perform their research single-handed, thus independently from other institutes. We call them *"maverick"*. Others, in turn, work collaboratively on specific research topics with a few selected research partners, which is a kind of an *elite circle* (e.g. the research institutes within the CRC 814, Germany). Furthermore, it is conceivable to pursue a strategy as a *team player*, striving for a strong research network with many research partners. Finally, an institute can also decide just to exchange knowledge between other institutes.
- Another significant strategic lever is the degree of *integration of companies along the AM value chain*. Integration of industry is a strategy an institute can pursue to increase the relevance of its research by addressing existing, up-coming and industrially relevant problems in AM. The integration can concern companies from different parts of the value chain.

Finally, the **third question a strategy answers is *how*** the institute intend to conduct its research work in the future. Therefore, six strategic variables were determined.

- A fundamental decision is how an institute intend to focus its research, meaning the ***research orientation***. As a branch pioneer, the institute can align its research to the purposes of a few selected branches. It has the expertise, to provide highly customized solutions for these selected branches. Another possible characteristics are functionally or technology-oriented strategies. These respectively mean aligning the research to specific functions like are lattice structures, gradient structures etc., or focusing advancing the technology itself.
- In addition, it is necessary to define the technological diversification strategy, meaning the ***technology-machine variety***, differentiating the number of different machines the institute possesses within different technologies.

Strategic Variable „What?“	Characteristics
1 Brand Image Brand image is the overall customers‘ perception of an institute’s public image. It indicates an organization’s character, highlighting its mission and vision to (potential) customers.	**A. High Quality in Education** The institute is mainly known for its outstanding expertise in education and training, propelling education of future AM-engineers or promoting/providing industry-wide training in Additive Manufacturing. Students, other universities as well as companies with a need for training revert to the expertise of the institute.
	B. High Quality and Relevance of Research The institute is mainly recognized for its outstanding research work and the scientific relevance of its results. The results may fundamentally advance scientific foundations, changing the understanding of existing processes. Within the research community, the institute is highly respected for linking scientific advancements to subsequent impacts.
	C. Problem-Solving as High Quality Service The institute has acquired a reputation for its outstanding problem solving competences/high quality services in the context of AM. The problem solving process encompasses understanding of the problem and its step-by-step transformation into a solution to achieve the desired outcome. Customers with challenging tasks in AM and potential applications revert to and rely on the institute’s competences.

Strategic Variable „Who?“	Characteristics
6 Interconnection within the Research Landscape The interconnection of institutes within the research landscape describes the degree of cooperation between different AM-institutes. Measures for the degree of cooperation are the number of partner institutes, collaborative research projects, joint conferences and publications as well as the extent of exchange in teaching (e.g. visiting professors).	**A. Team Player** The institute is strongly cross-linked within the research landscape and has many research partners. For instance, projects and conferences are carried out together with other institutes to establish an exciting research environment that links separate research outcomes. There is a profound exchange in teaching and joint publications.
	B. Maverick The institute does not have any cooperation with other research institutes at all. The own research work is not being shared with any other research facility. Performing research single-handed, the institute is independent from other institutes and does not pursue any knowledge exchange.
	C. Elite Circle The institute does not endeavor to cooperate with a large number of research institutes. Therefore, it performs projects and enters collaborative agreements on specific research topics with selected partners to increase scientific output and the impact for practice. There is no further exchange besides these specific projects.
	D. Knowledge Base The institute cooperates with other institutes in collaborative education and knowledge exchange. Thus, the collaboration is limited to joint teaching and publication of AM-knowledge.

Strategic Variable „How?“	Characteristics
11 Research Orientation Research orientation indicates the focus of the institute's research.	**A. Branch Pioneer** The research of the institute is oriented towards a few selected industries/branches that produce/intend to produce end-use parts via Additive Manufacturing. In general, these are Original Equipment Manufacturers, e.g. companies from the aerospace, automotive, medical industry etc. Based on its specific experience/know-how, the institute is a branch pioneer and is able to provide highly customized optimum solutions for these selected branches
	B. Orientation on Functionality The institute aligns its research along a few selected functions/product technologies across several industries. Exemplary functions are lattice structures, gradient structures etc. Orientation on functionality also includes requirement-specific research, e.g. investigations in increasing/enabling part stiffness, conductivity etc.
	C. Technology Orientation The institute is engaged in research on Additive Manufacturing technology itself. Technology orientation encompasses investigations on AM-processes and AM-materials as well as the development or advancements of respectively new or existing processes/materials.

Figure 3-8: Characteristics for three exemplary strategic variables

3.3.2 Consistent Strategy Variants

Based on the selected strategic variables and their characteristics, consistent strategy variants can be developed. As mentioned above, decision makers need a valid number of variants to plan their activities soundly. That is why we developed ten conceivable strategy variants for institutes involved in AM.

Consistent strategies encompass well-fitting characteristics: they are highly resource-efficient.

Using consistency analysis, the determined characteristics are combined to consistent strategies, representing combinations of characteristics that fit together well. To generate consistent strategies, each characteristics pair has to be reviewed on its compatibility. In this case, consistency stands for resource efficiency. An inconsistent strategy comprises characteristics which do not support each other; as a result, the strategy requires higher resource input, higher coordination and time effort. In a consistent strategy, all characteristics fit well together; financial and time efforts are minimized. Consistency analysis hence leads to a high number of thinkable combinations. To make this manageable, a clustering algorithm reduces the amount of combinations by summarizing those fit well together.

As a result, ten consistent strategy variants were developed in the project, differing in the ration of fundamental science and problem solving orientation. For instance, an institute can position itself as a problem solver, providing services for industry, or as a basic scientist, additionally providing academic education in AM. All ten strategy variants were precisely described.

An exemplary strategy variant is entitled as *Problem Shooter*. A Problem Shooter institute is known for problem solving competences to meet industrial requirements. An excerpt of further aspects characterizing the Problem Shooter are listed in the following.

- It is an intermediary between industry and research; it mainly collaborates with OEMs, offering engineering services and feasibility/benchmark studies, and with service companies that produce parts for OEMs.
- In this research, it addresses a few selected functions/product technologies across several industries (high branch diversification). The problem solver at least needs state-of-the-art equipment; it operates several machines from different AM-technologies ("Factory") to be able to service many customers with different problems concurrently. Aspirated collaboration forms of a problem solver are bilateral cooperation or long-term partnerships.
- The Problem Shooter is actively involved in shaping the AM-community, and endeavors to increase its visibility, especially in popular-scientific publications. As the institute does not pursue deep research work, it is not involved in adapting and developing machines and materials, or in education.
- The institute has a broad basic knowledge in all AM-technologies across all research fields; to increase technology expertise it closely cooperates with few selected institutes, fostering a creative dialogue ("Elite Circle"). Due to its knowledge in functional design, functional integration, process integration (of AM in conventional production lines) etc., the problem solver can be seen as an all-round talent.

The developed strategies range from "Problem Shooter" to "Fundamental Scientist": from industry focus to research focus.

To get a sound overview how the different strategies are position in relation to each other, a Strategy Map was created using the Multi-Dimensional Scaling (MDS), as shown in figure 3-9. MDS is a suitable way to visualize the positions of the strategies. MDS is a process derived from multi-variate statistics which generates a map where the strategies are visualized as bundles, indicated by the round shapes with Roman numerals in the figure. The distance between the bundles corresponds to the similarity of the bundles; the more similar the bundles, the closer to each other are their positions. Of course, the strategies can be differentiated by a number of underling dimensions; the mostly distinctive dimension – scientific vs. industrial orientation – is indicated in the Strategy Map. E.g. the *Problem Shooter* distinctively differs from a *Fundamental Scientist*, whereas the strategy *Science Chair* is comparably similar to the strategy *Fundamental Scientist*.

3.3.3 Competition Arena and Strategy Map

Strategies of research institutes were analyzed using the same strategic variables for their characterization.

The next question we asked ourselves is: Which strategies do the analyzed institutes pursue? Are the strategies comparable to the consistent ones developed in the project? The goal was a Strategy Map visualizing the ideal strategy variants as well as the strategies of the analyzed institutes. Following the same approach as used for generating the consistent strategy variants, the strategies of the research institutes are characterized. This means we used the same determined strategic variables for the characterization, specifying the characteristic a research institute pursue regarding each strategic variable. In this public study, we do not want to disclose any details about the research work of other institutes; therefore, the competition arena will be described anonymously. Please note that the numeration of the institutes was deliberately modified, thus does not correspond with the numeration in the research landscape. In addition, the number of institutes considered in the Strategy Map also deviates from that in the research landscape. This is due to internal decisions in the course of the project.

Three questions about "what", "who" and "how" need to be answered for each institute.

By contrasting the research institutes' strategies with the list of strategic variables and their characteristics, the individual strategies can be determined as corresponding combinations of characteristics. For instance, the following questions need to be answered in order to characterize the three strategic variables listed in figure 3-xy:

- **What:** By what kind of brand image is an institute characterized?
- **Who:** With whom is the institute interconnected within the research landscape?
- **How:** How is the range of research characterized

Institute-specific strategy profiles were determined and included into the Strategy Map.

After the individual specification of each strategic variables is completed for each institute, institute-specific strategy profiles are determined. In the Strategy Map, the research strategies of the institutes are visualized by the orange rhomb shapes. As we can deduce, the institutes' strategies do not necessarily correspond with the consistent strategies, as typically a strategy has been growing over the last years or the current position of an institute can also be in transition stage, meaning a shift from one strategy to another is performed.

The distance indicates the degree of similarities/differences between the strategies.

As previously mentioned, the distance describes the similarity/differences between the strategies. Institutes that are close to a strategy variant, pursue a nearly consistent strategy. E.g. C7 is close to strategy X which indicates that this institute is performing a strategy similar to the *Academy of Science*. To further diversification, the competition arena should be considered. What does this mean? C7 could take into consideration to shift to strategy X or III. Strategy variant X is characterized by a significantly tougher competition than strategy III, implying a low attractiveness of strategy X.

A recommendation could be to shift to strategy III, as in the matter of time and resources the effort is comparably low (indicated by the distance between C7 and III). Changing to strategy III requires monitoring C6 and C16. They might change their strategy to strategy III as well. Doing so, each institute has the possibility to find its own optimal strategic position.

Of course, each institute has to individually assess the attractiveness (e.g. competition intensity) and the effort in terms of time and money (e.g. available competences) for achieving a strategy for the selection of an optimally fitting strategy.

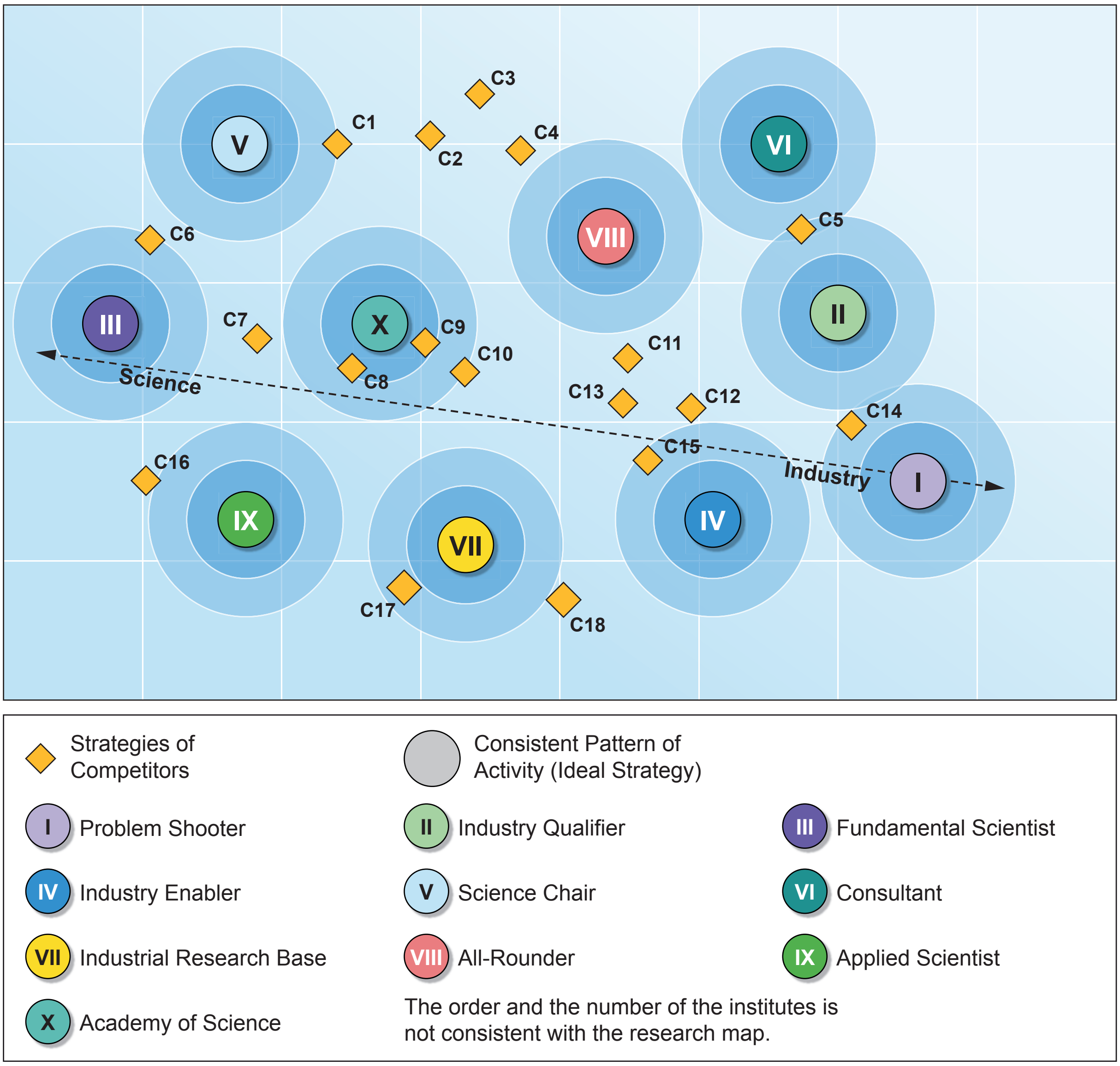

Figure 3-9: Strategy Map: Visualization of developed strategy variants and the current strategies in the research landscape

This analysis needs to be repeated regularly due to upcomming trends and future developments.

As already implied above, other institutes can also decide to shift their strategy. This is why it is crucial to observe these changes in the Strategy Map continuously. We recommend to repeat this process regularly. By comparing different time periods, trends in the research landscape can be derived and future developments can be anticipated. For instance, research strategies can change depending on the maturity level of a technology. In case of completely new technology, generally many institutes are working on fundamental scientific topics. As maturity increases, a shift towards applied research or even service-oriented research may occur. Concerning AM, it is discernible that many institutes are working on more “scientific” topics; others have already shifted to an industry-oriented strategy.

A Strategy Map represents a sophisticated overview on the competition in the research landscape.

Especially in research on an emerging technology such as AM, institutes would be well advised to revise their strategies regularly to tap upcoming requirements and trends. Simultaneously, a diversification is needed to not just copy other institutes' strategy, but to create a unique position. A Strategy Map allows an institute to gain a sound overview on consistent (optimal) strategy variants considering strategies of other (eventually competing) institutes.

How can these results now be leveraged to increase penetration of AM? Well, the developed Strategy Map obviously depicts that different strategies are conceivable; moreover, the conclusion emerge that different institutes follow different strategies (that do not necessarily correspond with the consistent ones). But what if we could take a closer look at this map and identify synergy effects that could contribute to advance AM further? What if we could increase research output and commonly transfer it into tangible outcomes that can be leveraged by industry?

3.4 Summary

In the project presented in this study, the Heinz Nixdorf Institute and the Direct Manufacturing Research Center (1) conducted an expert survey on the Future Relevance of Additive Manufacturing Research. (2) In a next step, all re-sults were merged in order to deduce white spots and success factors for strategies. (3) Finally, research strategies were developed and the competition arena was characterized. The results is a Strategy Map.

(1)The object of the survey was to identify the industry relevance of the research fields considered in the research landscape and the time of relevance. Highly relevant research fields with a short- or mid-term time of relevance, indi-cate an immediate need for action for the future penetration of AM. The experts' assessment shows that:

- The vast majority of the research fields are of high or at least medium relevance.
- Investigation on material quality, functional materials and new materials are assessed to be of outstanding relevance for the industry in the category *material research*.
- In *product research*, design rules, part tolerances and lightweight structures are highly relevant.
- For the other categories, for instance research on process tolerances and integration of AM into existing Manufacturing processes was rated to be significant.

(2) Merging the relevance of the research fields with the technologies' performance and the research intensity, *white spots* and resulting success factors giving hints on strategic levers were deduced, e.g.:

- Interconnection within the research landscape,
- Integration of companies along the value chain etc.

(3) These results enable a research institute to revise its currently pursued strategy and to find a success promising and future relevant strategic position in the research landscape. To develop consistent strategies, many strategic aspects deduced from the *white spots* and success factors – so called strategic variables – were taken into consideration. Those variables can be seen as levers to adjust the institute's strategy. Following VITOSTRA®, strategic variables were combined to ten consistent, and thus resource efficient strategy variants, ranging from a *Fundamental Scientist* to a *Problem Shooter*.

By contrasting these strategies with the strategies the analyzed institutes currently pursue, a Strategy Map was developed. As a result, it can be stated that:

- The institutes are well distributed around the ten consistent strategy variants.
- None of the institutes pursue a completely consistent strategy.

Each institute can assess the ten strategies concerning attractiveness and the effort required to perform a shift. Question that arise from these results in general for the AM landscape are the following:

- How can we use this diversified distribution of the institutes' strategies to generate synergy effects?
- And thus, how can we benefit from a stronger collaboration in order to commonly leverage increased and tangible research outcome for the industry – and thereby to increase the penetration of AM in general?

All in all, the results should inspire to think about how we can design the AM research landscape in terms of technological levers – basically represented by the highly relevant research fields for each technology, as well as in terms of organizational levers – the required infrastructure for enhancing the technological levers.

4

Conclusion and Outlook

“Thinking ahead the Future of Additive Manufacturing – Exploring the Research Landscape” study reveals the Research and Strategy Map for selected AM research institutes. The study comprises a sophisticated overview on the overall proceeding in the project “Research Strategies for Additive Manufacturing Technologies“, and outlines the project’s results in extracts. Comprehensive results are part of the confidential study that is accessible for DMRC partners.

The status quo, current initiatives and future trends were analyzed.

The present study firstly provides an overview on AM. Therefore, actual developments are briefly described, addressing current initiatives and up-coming trends, influencing AM and vice versa. In addition, the preceding project is presented – lining out future scenarios, applications and innovation roadmapping of required advancements.

The AM Research Map indicates the research intensity in different research fields.

Secondly, the AM research landscape was analyzed and an Additive Manufacturing Research Map was developed. The Map indicates the intensity of research activity of selected research institutes, differentiating various research-field/technology-combinations. For each category of technologies, a research activity profile was created.

White spots in the research landscape were deduced and validated in an expert survey.

A Strategy Map visualizes ten cosistent research strategies and the institutes’ positions.

By merging these results with the future relevance of the research fields and the technologies’ performance in these research fields in a third step, so called *white spots* were deduced. The future relevance was validated as part of an expert survey. Using the *white spots* which basically represent highly relevant research fields that however are not addressed in current research projects, strategic levers for research strategies emerged, e.g. the *interconnection within the research landscape* and *integration of companies along the value chain*. Based on this, consistent research strategies were developed, and the institutes’ strategies were analyzed as well. The results were consolidated in a Strategy Map, visualizing the institutes’ positions in relation to the consistent strategies.

Question: How can potentials be leveraged to accelerate the penetration of AM.

A number of conclusions emerge in the present study. All in all, we can state that AM is definitely a disruptive technology which is progressively permeating diverse markets. The technology is certainly capable to trigger major upheavals reshaping supply chains and business models over the next decade. But the question we asked in this project is: How can the research landscape contribute to leverage a more beneficial output for the industry, and thus to accelerate the penetration of AM. The analysis of the research landscape shows that there are many research initiatives, many institutes are dealing with AM and a number of different strategies are discernible. Hence, we are doing a lot.

However, some research fields are repeatedly explored which costs time and money and does not necessarily contribute to advance the technology. Moreover, there are still some *white spots* in the research

A closer cooperation can enable synergy effects and thus a higher value for the indstry can be leveraged.

landscape that could be addressed more extensively, and there is still potential regarding the infrastructural levers, meaning:

- What if we would, for instance, realize synergy effects within the research through a stronger interconnection in the landscape or
- What if we would collaborate more closely along the whole value chain?

Doing so – we are sure – we definitely could leverage a higher value for the industry, and thus increase the penetration of AM.

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A1

VITOSTRA®

In strategic leadership, identifying strategic directions is not trivial. Usually, the available amount of information is stunning high. Due to this and the typical time pressure, decision makers are often satisfied if one plausible strategy option results. In contrast to this, the quality of strategy development increases if more than one strategy option is developed for being taken into consideration [Fe96].

A strategy is founded on a number of entrepreneurial activities. According to PORTER, the crux of matter is not the kind of activities, but rather their combination which leads to a successful position in the competitive environment. Thus, the success of a strategy crucially depends on its being individually tailored to fit the situation [Por97]. MARKIDES stated that successful companies do not try to copy the activities of their competitors, they rather follow a unique strategy enabling them for playing "their own game" and thus being a step ahead of respective competitors [Mar02].

Due to this and the fact that decision makers need alternatives, we established a discursive approach for developing intelligent and consistent strategy variants called VITOSTRA®. Following the principle of the Scenario-Technique, the core of this method is the consistency analysis which allows creating combinations of strategic variables' characteristics. Strategic variables represent strategic levers and the alternative characteristics are the different conceivable positions for the levers the company can adjust in a strategy [GPW09]. Exemplary variables e.g. for producing companies are the product program, the manufacturing range, the sales channels etc. VITOSTRA® can be explained by a phases/milestone diagram which consists of 5 phases, as shown in figure A1. In the following, the phases are described in detail.

Phase 1: Definition of Business

The description of the business frames the field a company can position itself within and the group of competitors in this field. Initially, it is of great importance to specify the degrees of freedom for the development of the strategy - the so called strategic variables/levers. Within a company and its competition arena, strategic variables can be found e.g. in the three search fields *Who?* (who are our customers), *What?* (what are our products and services) and *"How?"* (how do we provide our products and services). All of these strategic variables represent strategic levers that can be adjusted to different positions, thus representing alternative options for action. According to MARKIDES these fields give answers for the strategy development [Mar02]. A strategy defines which products or services a company offers, the customers respectively the different market segments the company addresses and how the company fulfills the customer requirements.

The definition of the business strongly influence of the resulting strategies. The narrower the definition is formulated, the easier it is to implement the new strategy; however, these strategies are less innovative than those which are based on a broader definition. The best way to succeed is to start with an explicit definition. In case that not enough strategy alternatives with a high success potential can be developed, the definition should become broader.

Phase 2: Analysis of Strategic Options

In a subsequent step, the analysis of strategic options occurs. Firstly, strategic variables are identified; secondly, conceivable characteristics for each variable are worked out. This is the central and creative part of the strategy development, as thereby the elements of the strategies are generated; these elements directly contribute to the quality of the strategies.

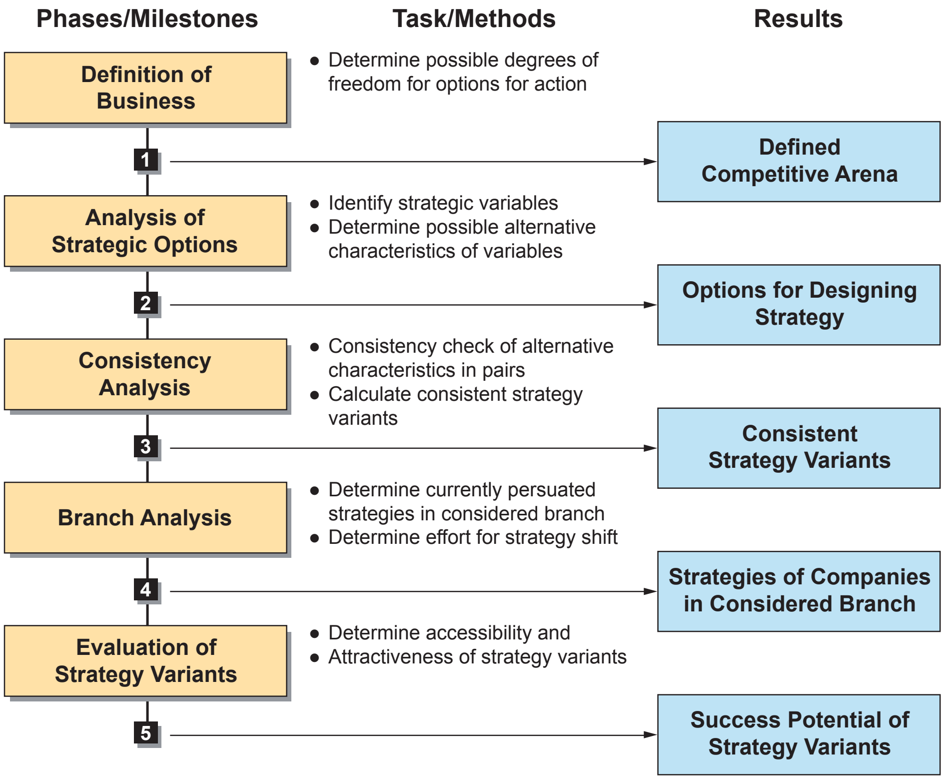

Figure A-1: Proceeding of VITOSTRA®

Ideas for strategic variables are often already resulting from the foresight process which is typically should be a preceding step in strategic leadership.

Variables describing the *Who?* search field can be deduced from a company's market segmentation. To answer the *What*? question, product features satisfying customer demands are identified and transformed to strategic variables, for instance by using Quality Function Deployment [Ehr03]. Here, the product core (e.g. materials, technical functions or performance data) is focused. For answering the *How*-question, PORTER's classical value chain approach can be used as starting point [Por97].

In a next step, conceivable characteristics are developed for each strategic variable. Just to provide an example, a strategic variable *manufacturing range* can be characterized by a *high share of production*, *system supplier*, and a *low share of production*. The variables and their characteristics are described in detail. In this step, the challenge is to identify especially those characteristics which are currently not characteristic for competitors' strategies [GPW09].

Phase 3: Consistency Analysis

In the consistency analysis, strategies are developed based on the formulated characteristics. A strategy is basically a combination of characteristics that fit well together. The evaluation of the consistency between the different characteristics has to be executed by the members of the strategy development team. To generate internally consistent strategies, each characteristic pair has to be reviewed on its compatibility. This pairwise consistency assessment occurs in a consistency matrix. Within the consistency matrix, consistency ratings only need to be entered on one side, as the relation between the characteristics is not directed. For the evaluation of the consistency, we use the following assessment scale:

1 = Total inconsistency, i.e. both characteristics are mutually exclusive and cannot pursued concurrently in a strategy;

2 = Partial inconsistency, i.e. both characteristics contradict each other partially. Their joint occurrence

reduces the efficiency of a strategy and is not recommendable;

3 = Neutral or independent, i.e. either the characteristics do not influence each other or their joint occurrence does not influence the efficiency of a strategy;

4 = Partial consistency, i.e. both characteristics complement one another well and thus can well be combined in the same strategy;

5 = Total consistency, i.e. both characteristics go hand in hand or even cause each other (due to the implementation of one characteristic, the implmentation of the other characteristic is crucial.

The consistency evaluation of each characteristic pair is based on subjective assessment. Particularly in larger projects, several consistency matrices are to be completed. The deviations resulting from the various evaluations, allow conclusions on problems of comprehension and different estimations of consistency. The discussion associated with the synchronization of the different consistency matrices per se represents a value creation in a strategy development project. The consistency analysis is automatically performed by the applied scenario software.

Calculating all combinations, focusing the most consistent ones and using a cluster algorithm, several consistent and therefore promising strategy variants are resulting. A strategy variant contains (at least) one characteristics from each strategic variable. The information about which characteristics are included in which strategy variants can be deduced from an automatically generated characteristics list.

Phase 4: Branch Analysis

In particular with regard to the subsequent assessment of the developed strategy variants, the object of the branch analysis is to answer the following questions:

- Which strategy does the considered company as well as its competitors pursue?
- Is the strategy the company currently pursue consistent, i.e. does it correspond with one of the developed (ideal, consistent) strategy variants? If no: Which combinations of strategic decisions have led to an inconsistent strategy?
- In which characteristics does the pursued strategy differ from the developed strategy variants?
- How much effort (financial and time) does it take to switch from the currently pursued strategy to one of the developed strategy variants?
- Is there any unique strategy variant that is not pursued by any competitor?

The first step on the way to answer the questions is to characterize the strategies in the competition arena on the ba-sis of the determined strategic variables. Using Multi Dimensional Scaling, these results can be visualized in a Strate-gy Map. Figure A-2 shows an example of a resulting Strategy Map. The map shows the strategies of the company and its competitors in relation to each other as well as the developed, consistent strategy variants. The distance ba-sically represents the contextual difference of the strategies (i.e. its characteristics) and indicates the effort (in terms of time and money) a shift from one strategy to another one would require.

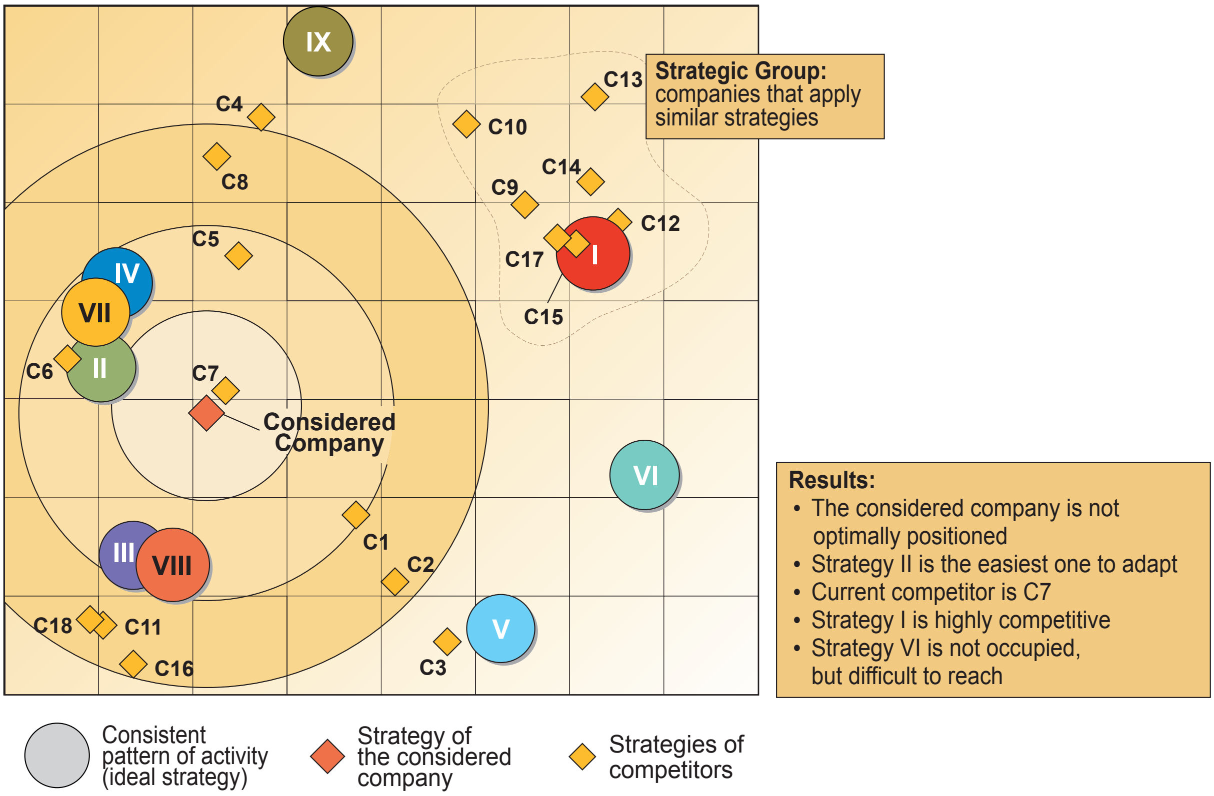

Figure A-2: Exemplary Strategy Map: Visualization of the competitive arena, including developed strategy variants and the current strategy/strategies respectively of the considered company and its competitors

Phase 5: Evaluation of Strategy Variants

The goal of this final step is to identify the strategy variant with the greatest success potential. The developed strategy variants, the currently pursued strategy of the considered company as well as the strategies of the competitors are the basis for the assessment. We consider two criteria:

- Attractiveness of strategy variants: To determine the attractiveness the expected market potential and competition intensity as well as compatibility with a company's strategic goals are evaluated.
- Accessibility of strategy variants: The accessibility takes into account the time and financial effort required to perform a shift from the current strategy to one of the strategy variant. Moreover, potential entry barriers are considered.

Assessing each strategy variant regarding these criteria allows selecting the most promising strategy variant: the higher the attractiveness of a strategy variant and the easier it can be achieved, the higher the success potential is. Another important aspect for the assessment is the establishment of a monitoring process for the competition arena. The monitoring process can be structured on the basis of strategic variables; thus, at selected future time frames, the Strategy Map can be updated. Thereby, the changes of the competitors' strategies can be monitored continuously.

For more information on the VITOSTRA® technique please see the following book:

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

A2

List of Abbreviations

ABS	acrylonitrile-butadiene-styrene plastics
AdAM	Advanced Additive Manufacturing, University of Sheffield
AM	Additive Manufacturing
AMC	Advanced Manufacturing Center, University of Texas in Austin
AMRG	Additive Manufacturing Research Group
CAD	Computer Aided Design
CRC	Collaborative Research Center 814 – Additive Manufacturing
Ctrl	Control
DFG	German Research Foundation
DM	Direct Manufacturing
DMRC	Direct Manufacturing Research Center
EPRSC	Engineering and Physical Sciences Research Council
FDM	Fused Deposition Modeling
FLM	Fused Layer Modeling
IFAM	Fraunhofer Institute for Manufacturing Technology and Advanced Materials
iLas	Institute of Laser and Systems Technologies
ILT	Fraunhofer Institute for Laser Technology
irpd	Institute for rapid product development
KPI	key performance indicators
LS	Laser Sintering
LZN	Laser Center North
MEMS	micro-electromechanical systems
MID	Molded Interconnection Devices
NAMII	National Additive Manufacturing Innovation Institute
NASA	National Aeronautics and Space Administration
NDI	non-destructive inspection
NIST	National Institute of Standards and Technology
PBF	Powder Bed Fusion

PMA	Production engineering, Machine design and Automation, University Leuven
R&D	Research and Development
RM	Rapid Manufacturing
RPC	Rapid Prototyping Center, University of Louisville
RTC	Rapid Technology Center, University of Duisburg
SLA	Stereolithography
SLM	Selective Laser Melting

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