3D Printing

A Qualitative Assessment of Applications, Recent Trends and the Technology's Future Potential

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Studien zum deutschen Innovationssystem
Nr. 17-2015

Center for Digital Technology and Management (CDTM), München

February 2015

Diese Studie wurde im Auftrag der Expertenkommission Forschung und Innovation (EFI) erstellt. Die Ergebnisse und Interpretationen liegen in der alleinigen Verantwortung der durchführenden Institute. Die EFI hat auf die Abfassung des Berichts keinen Einfluss genommen.

This study was conducted on behalf of the Expertenkommission Forschung und Innovation (EFI). The results and interpretations are the sole responsibility of the institute conducting the study. The EFI exercised no influence on the writing of this report.

Studien zum deutschen Innovationssystem

Nr. 17-2015

ISSN 1613-4338

Publisher:

Expertenkommission Forschung und Innovation (EFI)

Geschäftsstelle

c/o Stifterverband für die Deutsche Wissenschaft

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This study was conducted by the Center for Digital Technology and Management (www.cdtm.de), a joint institution of the two universities in Munich, the Ludwig-Maximilians-Universität München (LMU) and the Technische Universität München (TUM). CDTM offers the interdisciplinary add-on study program „Technology Management“, which is part of the Elite Network of Bavaria. Students from various study backgrounds with creative ideas, great motivation and an entrepreneurial mindset are offered the tools to put their ideas into practice.

The study is partially based on results of the CDTM elective course “3D Printing” in Spring 2014. Therefore, findings of this study are an emergent product of the student’s work and additional research conducted by the main authors.

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Abbreviations

ABS	Acrylonitrile butadiene styrene
AM	Additive manufacturing
CAD (file)	Computer-aided design file
CPS	Cyber-physical-system
FDM	Fused Deposition Modeling
LENS	Laser Engineered Net Shaping
LM	Layer Manufacturing
NAMII	National Additive Manufacturing Innovation Institutes
RM	Rapid Manufacturing
RP	Rapid Prototyping
RT	Rapid Tooling
STL	Standard Triangulation Language
SLA	Stereolithography
SLS	Selective Laser Sintering

0. Executive Summary

Additive manufacturing (AM) or *3D printing* is currently one of the most discussed emerging technologies coming to market with a potentially disruptive power. The terms *additive manufacturing* (AM) and *3D printing* describe production processes in which a solid 3D structure is produced layer by layer by the deposition of suitable materials via an additive manufacturing machine. After around 30 years in the making, 3D printing is about to move from being an industrial rapid prototyping technique to becoming a mainstream manufacturing procedure used by industry and consumers alike. However, the question *in which area* and *to which extent* this emerging technology will disrupt state of the art practices is far from trivial.

The goal of this report on behalf of the Expert Commission of Research and Innovation is threefold: First, to sketch the emerging 3D printing landscape, explore key trends and the technology's potential. Second, to shed light on 3D printing market dynamics and framework conditions both in Germany and in other countries. Third, to translate the findings into recommendations that can serve as a basis for the Expert Commission's policy report. From a methodological perspective, the study at hand presents a knowledge synthesis based on a mix of research methods: (1) an extensive desk research of over 250 documents comprising both academic as well as grey literature; (2) 17 interviews with representatives from science and industry; (3) eight small case studies that provide detailed insights into certain areas of interest; (4) several workshops and discussions that were held during the elective course on 3D printing at the Center for Digital Technology and Management (CDTM) in Munich in 2014.

In the course of this study, different areas of application of AM technology are explored and put into context: (1) AM in the industrial area, (2) AM in the healthcare and wellbeing sector, and (3) AM in the consumer market.

At first, various technical opportunities and challenges related to AM processes are elucidated. It becomes clear that AM has a range of advantages compared to conventional production processes. Especially new degrees of freedom in product and process design open up opportunities for increased part complexity, material savings and weight reduction. Furthermore, the direct connection between digital part design and manufacturing allows leaner production chains and enables mass customization at no or little additional costs. At this point in time, however, these opportunities are still moderated by various technical challenges that need to be overcome to make AM applicable for mainstream mass production purposes. Thereby, a major hurdle lies in the availability of appropriate printing materials in both the industrial and the healthcare sector. The amount to choose from is still limited, and the printed quality, which typically requires post-processing, is in some cases inferior to conventionally produced items. Also in the consumer market, a broad dissemination of 3D printers is still hindered due to technical challenges. Many desktop printers are still slow, require expensive printing material and deliver insufficient printing quality. However, considering the speed of development in the desktop 3D printing market, it is likely that the quality of the devices will keep on increasing in the near future.

The striking aspect about additive manufacturing technology is the wide range of possible applications, reaching from industrial manufacturing, medical manufacturing and 3D bioprinting with living cells to 3D home printing with desktop applications. The different areas, however, differentiate in terms of maturity.

(1) In the *industrial area*, AM is already an established manufacturing method in some sectors and has been used for over 30 years – so far predominantly for parts production and tooling. Recent R&D advancements, however, have triggered two major trends: (1) an advancement from rapid prototyping to rapid manufacturing, and (2) a facilitation of mass customization of end-products. In this way, AM technology can be used for new purposes and finally enters the stage of end-product manufacturing. Thus, in the long-term, AM technology may change the relationship between producers and consumers significantly. Apart from modes of mass customization, AM – especially when applied as rapid manufacturing – might also serve as an enabling technology for digital manufacturing. This becomes particularly interesting when looking at the German vision of an Industry 4.0. Companies increasingly start to establish structures of Cyber-Physical-Systems and try to digitalize their processes as far as possible. With its flexibility, AM technology has the potential to become an essential tool in the CPS arena. Nevertheless, there are also sceptic voices with regard to the potential of 3D printing for industrial purposes in general and large-scale manufacturing in particular. Critics argue that it is highly unlikely that 3D printing can replace the mass production of parts or components in a short to medium time span due to remaining technical challenges.

    The findings with regard to industrial applications of AM technology are supplemented by four case studies. The first case study presents the potential of AM to produce complex parts based on the example of the tooling industry. The second case study deals with the aerospace industry, in which AM can be used to reduce the weight of components leading to significant fuel savings. The third case study deals with the car industry, in which applications of AM could decrease assembly costs. The fourth case study finally shows that AM can also be used as an enabler of customization and possibly even mass customization in the footwear industry.

(2) Most interviewed experts agreed that of all areas, 3D printing bears the highest potential for a fundamental market disruption in the *healthcare sector*. There, AM is probably more needed than in any other application area as it enables individualized design, for instance for surgical guides, implants, prostheses, ortheses or tissues. Akin to all other AM areas, however, 3D printing applications vary in terms of technological maturity in the field of healthcare, too. Whereas 3D printing is already common practice in dentistry, 3D bioprinting of tissues and living cells is still at a stage of fundamental research and far from practical application. The same counts for 3D food printing, a topic that mainly gained recognition due to playful applications like the printing of cakes or pasta with special design pattern. Nevertheless, in the long-term, 3D food printing

could be used for creating artificial food for people with swallowing problems or special nutritional needs. In this way, 3D food printing might contribute to a higher quality of life for certain target groups.

(3) The latest development in 3D printing, which also inflamed the recent hype around the topic, is certainly *desktop 3D printing in the consumer market*. With the expiration of relevant patents, a plethora of different desktop 3D printers has entered the consumer markets. With the technology becoming faster, more reliable and cheaper, the low-cost personal 3D printer market experienced a tremendous growth in the last years. This development coincides with improving design capabilities, as well as an improving ability of individual users to combine and coordinate their innovation-related efforts via internet. In other words, during the past years, it got continuously easier for consumers to get what they want by designing products for themselves – a development that inflamed the so-called *maker movement*. Nevertheless, to date, makers remain a comparably small niche and the future development of home 3D printing is far from certain. Only the next years will reveal in how far individual behavior of a critical mass of people will be changed by 3D printing. As stated, this is mainly dependent on technical advancements in home 3D printing. Hardware manufacturers, however, have recognized deficiencies and have begun to develop desktop models with significantly bigger chamber sizes.

Bringing the three fields – AM for industrial production, healthcare and in the consumer market – together, a macro-environmental assessment revealed that the market for AM technology and related services is still far from being saturated and offers significant financial potential in the future, both for Germany and on a global scale. Furthermore, it is likely that AM could also positively contribute to other important pillars of society: first, to society in general by empowering people and consumers around the globe and thereby contributing to the field of sustainable human development; and second, to environmental protection by offering possibilities for emissions savings and waste reduction along the life-cycle of products. Nevertheless, it became also evident that some of the main factors that currently impede a broader dissemination and adoption of 3D printing technology are located in the legal and regulatory area. There are many open questions in this field, reaching from issues of intellectual property to complicated procedures for part approval. Thus, to enable a thriving 3D printing landscape, these regulatory challenges need to be overcome in order to set the right boundary conditions.

To put it in a nutshell, even though 3D printing may not inflame the next industrial revolution, it is definitely an important manufacturing technology that can have a huge impact on certain sectors. This notion even becomes stronger when comparing the potential benefits of AM with the long-term high-tech strategy of Germany as a global leader in industry and manufacturing. It is likely that AM will strongly influence the mechanical engineering, automotive, aerospace and medical engineering industries, which are all of high importance for Germany. Furthermore, upcoming fields like 3D bioprinting offer opportunities to establish new fields of expertise and global leadership. Thus, especially for Germany the topic of 3D printing is of very high relevance and has a tremendous potential.

The international comparison of AM research activities and public funding around the world showed, however, that in Germany public support of AM technology is not as strong as in other countries. Especially the USA and China aim for a pioneering role in that area and have adopted large budgets for research activities, innovation and startup funding. Thereby, both nations do not only focus on AM for industrial applications, but also specifically support the arising maker movement by fostering the establishment of public maker spaces and facilitating access to the technology.

To secure its competitive advantage as the world's leading high-tech nation, Germany should promote AM technology and ensure public support for research and innovation programs that go beyond EU programs. Therefore, 10 policy recommendations have been formulated that can serve as a basis for further proceedings.

Area	Recommendation
Part I: Unleashing the technology's full potential	I.I Public funding for fundamental and applied research
	I.II Establishment and support of interdisciplinary and trans-regional 3D printing clusters
Part II: Defining framework conditions for an emerging 3D printing market	II.I Establish an expert group to clarify open regulatory and legal questions
	II.II Investigation of new solutions in the area of intellectual property
	II.III Establishing mechanisms for consumer protection and quality assurance
	II.IV Developing new mechanisms for standardization and product approval
Part III: Enabling a thriving 3D printing landscape	III.I Enhancing general visibility of and accessibility to 3D printing technology
	III.II Integration of 3D printing in education agendas for schools and universities across disciplines
	III.III Establishing a 3D printing information platform for end-users
	III.IV Fostering entrepreneurship in the area of 3D printing

1. Introduction

Bits are thrilling, but when it comes to the overall economy, it's all about atoms.
Chris Anderson in 'Makers', 2012

1.1 3D printing: The next industrial revolution?

Additive manufacturing or *3D printing* is currently one of the most discussed emerging technologies coming to market with a potentially disruptive power. After around 30 years in the making, 3D printing is about to move from being an industrial rapid prototyping technique to becoming a mainstream manufacturing procedure used by industry and consumers alike. Looking at the international landscape of technology, innovation and entrepreneurship, developments around 3D printing have gained momentum resulting in a plethora of news and raising high expectations regarding the technology's potential. During the past years, the low-cost (< 5000$) personal 3D printer market experienced a tremendous growth with an average rate of 346% each year from 2008 to 2011. In 2013, US President Obama acknowledged the disruptive power of 3D printing in his second State of the Union address and announced his plans to create National Additive Manufacturing Innovation Institutes (NAMII). And in early 2014, home 3D printing was one of the core topics at the International Consumer Electronics Show (CES) in Las Vegas. Various researchers and industry commentators even argue that 3D printing technology has the potential to create a new type of industrial revolution (e.g. Anderson, 2012; Markillie, 2012; Barnatt, 2013). By 2021, global sales of 3D printing products and services are expected to grow up to $10.8 billion compared to $1.7 billion in 2011 (Wohlers Associates, 2013). Also within the European Union, first harbingers of a 3D printing movement can be observed. Examples are the Munich based EOS GmbH and Voxeljet AG as a global leaders for e-manufacturing solutions since 1989, the Belgium based company Materialise NV, or the Dutch Desktop 3D printer manufacturer Ultimaker.

The striking aspect about additive manufacturing technology is the wide range of possible applications, reaching from industrial manufacturing, medical manufacturing and 3D bioprinting with living cells to 3D home printing with desktop applications. The different areas, however, differentiate in terms of maturity. As the Gartner Hype Cyle (2014) – a graphical representation of a technology's life cycle stage – indicates, 3D printing in the industrial area is already an established technique, whereas 3D printing in the consumer area or 3D bioprinting are at earlier stages of development (see fig. 1). Thus, the future of additive manufacturing technology is still uncertain and dependent on the specific application area. Consequently, the question in which area and to which extent this emerging technology will disrupt state of the art practices is still far from trivial.

The goal of this report on behalf of the Expert Commission of Research and Innovation is threefold: First, to sketch the emerging 3D printing landscape, explore key trends and the technology's potential. Second, to shed light on 3D printing market dynamics and framework conditions both in Germany and in other countries. Third, to translate the findings into recommendations that can serve as a basis of the Expert Commission's policy report.

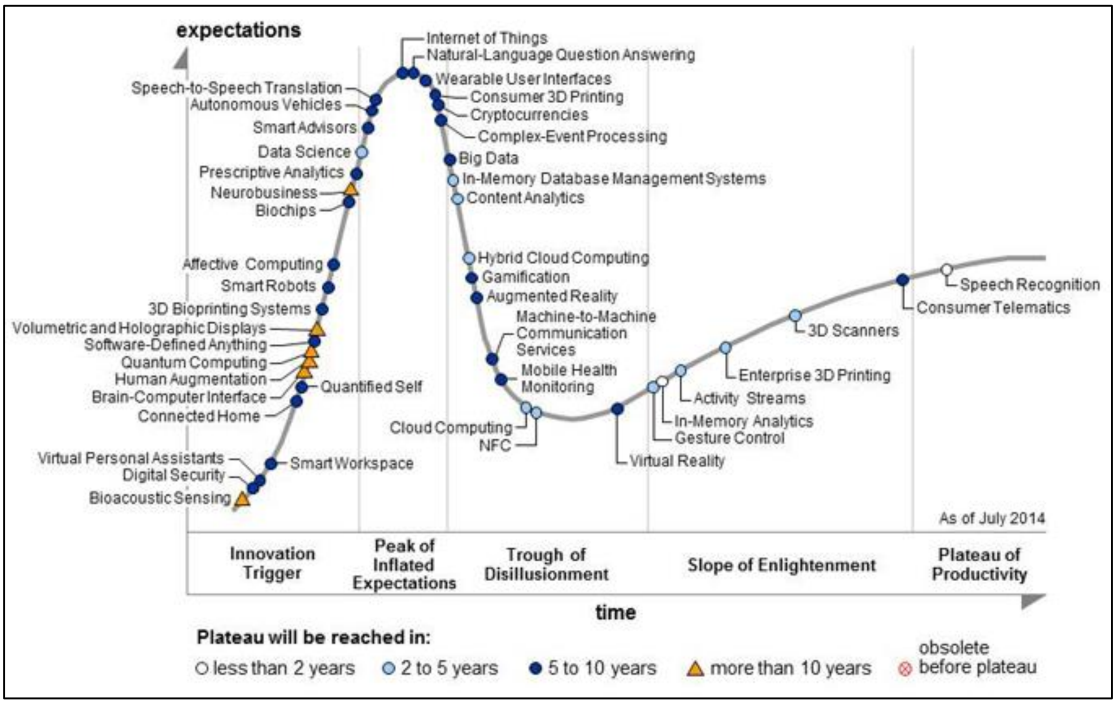

Figure 1: Gartner's 2014 Hype Cycle for Emerging Technologies. Source: Gartner, 2014.

1.2 Research methodology

This report presents an exploratory research inquiry based on a mix of research methods.

Desk research

All findings are based on an extensive review of relevant scientific articles, media sources as well as grey literature. Since 3D printing is a new and partially unexplored topic, academic literature is still scarce. Moreover, large industry players as well as a global open-source movement with thousands of individual innovators have significantly influenced the advancement of 3D printing technology. To ensure topicality of this report, we did not limit the investigated literature and sources for this research to academic literature from peer-reviewed journals only, but deliberately included up to date publications such as articles from relevant tech magazines and reviews, as well as corporate reports and press releases. In the end, 260 sources from different media and journals have been taken into consideration to draw a holistic picture of current developments in the 3D printing ecosystem. Table 1 provides an overview of the used sources.

Table 1: Overview of sources. Source: Own illustration.

Source Category	Type of Source	Number
Academic Literature	Articles from peer-reviewed journals	44
	Monographs, specialist books and university publications	26
	Conference proceedings & working papers	9
Corporate Publications	Reports	6
	White papers & case studies	4
	Other publications (website, press releases etc.)	42
Media Publications	Tech reviews and specialist magazines (e.g. Tech Crunch, Harvard Business Review etc.)	53
	Other news publications (Forbes, BBC; CNN etc.)	52
Other	Government publications, patents, non 3D-printing related articles, etc.	24

Expert interviews

For purposes of triangulation, 17 interviews with experts both from science and industry have been conducted to enhance the internal validity of the research output and to allow the generation of a comprehensive picture of the research phenomenon. Table 2 displays a list of the institutions and companies that were involved in the expert interviews. The table shows that the interviewees represent a balanced sample from different areas of interest. The interviews followed a semi-structured design based on guidelines that have been derived from a literature review previous to this report.

Table 2: Institutions that took part in the interviews for this report. Source: Own illustration.

Institution	Focus Area	Cited as
Julius-Maximilians-Universität Würzburg, Lehrstuhl für Wirtschaftsinformatik und Systementwicklung,	General	Interview 1
Roland Berger Strategy Consultants	General	Interview 2
Airbus Group, Global Innovation Networkers	Industrial applications	Interview 3
EOS GmbH	Industrial applications	Interview 4
RWTH Aachen, Lehrstuhl für Lasertechnik	Industrial applications	Interview 5
Voxeljet AG	Industrial applications	Interview 6
Fraunhofer Institute for Interfacial Engineering and Biotechnology	Medical applications and bioprinting	Interview 7
Klinik und Poliklinik für Mund-, Kiefer- und Plastische Gesichtschirurgie, Universitätsklinikum Würzburg	Medical applications and bioprinting	Interview 8
Institute of Health and Biomedical Innovation (IHBI) at Queensland University of Technology	Medical applications and bioprinting	Interview 9
Lehmann & Voss & Co. KG, Hamburg	Materials	Interview 10
Fablab Munich	End-user space	Interview 11
Fraunhofer Institute for Manufacturing Engineering and Automation	End-user space	Interview 12
RWTH Aachen, Chair of Technology and Innovation Management (TIM)	End-user space	Interview 13
AIO Robotics	Startup	Interview 14
Wamungo	Startup	Interview 15
Max-Planck-Institute for Competition and Innovation	Intellectual property law	Interview 16
Technical University of Munich, Chair of Mechanical Deformation and Founding	Legal aspects and industrial applications	Interview 17

Case Studies

The chapters dealing with industrial applications of additive manufacturing (chapter 3.1) and home 3D printing (chapter 3.3) are complemented by several case studies. The case studies provide detailed insights the different areas and thus increase the internal validity of the study. Table 3 provides an overview of the included case studies.

Table 3: Overview of case studies. Source: Own illustration.

Section	Case Study	Chapter
Industrial applications	Additive manufacturing for injection molding dies	3.1.2.1
	Additive manufacturing in the aerospace industry	3.1.2.2
	Additive manufacturing in the car industry	3.1.2.3
	Additive manufacturing in the footwear industry	3.1.2.4
Corporate Publications	3D printer manufacturer	3.3.2.1
	3D model marketplaces and search engines	3.3.2.3
	E-commerce: 3D printed object marketplaces	3.3.2.4
	In-store 3D printing services	3.3.2.5

Interactive discussions and workshops

This report was written by a team of the Center for Digital Technology and Management, a joint institution of the two universities in Munich, the Ludwig-Maximilians-Universität München (LMU) and the Technische Universität München (TUM). CDTM offers the interdisciplinary add-on study program *Technology Management*. The content of the report is partially based on results of the elective course on 3D printing that was offered for CDTM students in spring 2014 and organized in cooperation with the Munich Max-Planck-Institute for Competition and Innovation. Therefore, several findings of this study are an emergent product of the work of 18 CDTM students and three doctoral candidates, as well as insights from workshops and fruitful discussions with researchers and industry experts during the course.

1.3 Report structure

Chapter 2 provides the theoretical and technical foundation for the report and defines key terms. It includes an explanation of different additive manufacturing techniques as well as a patent-based review of the technology's development during the past 30 years.

Chapter 3 is dedicated to different application areas of 3D printing. It contains three sub-chapters, each of them exploring another area. Chapter 3.1 examines the current state of 3D printing in industrial applications. Chapter 3.2 draws attention to 3D printing in the area of health care. Finally, chapter 3.3 investigates the so-called *maker movement* and end-user applications of 3D printing.

Chapter 4 puts the research findings into broader context and assesses macro-environmental aspects with regard to 3D printing. The chapter starts with an overview of public support and respective research agendas both in Germany and in other countries (chapter 4.1). This assessment is followed by an economic evaluation of 3D printing technology (chapter 4.2). Afterwards, possible socio-economic impacts are described (chapter 4.3). Chapter 4.4 draws the reader's attention to arising challenges in the area of regulations and intellectual property. Finally, chapter 4.5 provides a literature-based environmental life-cycle assessment of 3D printed products.

Chapter 5 merges the different chapters. Chapter 5.1 summarizes and consolidates the research findings and provides a final evaluation of the potential of 3D printing. Based on these findings, policy recommendations for further actions have been developed, which are described in chapter 5.2.

2. Fundamentals of 3D Printing Technology

2.1 Definition of 3D printing

The terms *additive manufacturing* (AM) and *3D printing* describe production processes in which a solid 3D structure is produced layer by layer by the deposition of suitable materials via an additive manufacturing machine. In contrast to other manufacturing procedures, such as machining and stamping that fabricate products by removing materials from a larger stock or sheet of material, AM creates the final shape by adding materials (Huang, Liu, Mokasdar & Hou, 2013). The entire AM process includes the digital development of a computerized 3D model or data set containing the complete geometrical information, as well as the transformation of the data into a physical model (Hanemann et al., 2006; Huang et al., 2013). In this report, the terms *additive manufacturing* and *3D printing* are used synonymously and serve as umbrella terms for all technologies and applications.

2.2 Chronology of additive manufacturing technology

2.2.1 Technological inventions and patents

The early roots of AM technology go back to 19th century techniques of photosculpture and topography. As early as 1859, François Willème developed a process to create a three-dimensional representation of an object by simultaneously capturing image data with 24 different cameras, one every 15 degrees. In April 1890, Joseph E. Blanther filed a patent on manufacturing contour relief-maps by using different layers of wax plates. These examples of early 3D printing forerunners provide a first backdrop for the developments of the past 50 years. The history of modern AM, however, begins with the advent of the main current 3D printing techniques, namely laser sintering processes, stereolithography and fused deposition modeling in the late 1980ies. Table 4 displays a chronological timeline of the most important AM patents that have been filed between 1979 and 2000. This overview is non-exhaustive, but indicates the major inventions and developments in the field.

Hideo Kodama of Nagoya Municipal Industrial Research Institute published the first article about a functional photopolymer rapid prototyping system in 1981. In 1984, Charles W. Hull invented the technique of stereolithography, which uses a laser to selectively harden a layer of plastic in a pool of fluid base material. The patent for this idea was issued in 1986. In the same year, Hull founded the company 3D Systems, which is to date one of the global players and pioneers in the 3D printing market. In 1992, 3D Systems started to sell their first machines that enabled end-users to use stereolithography in order to produce prototypes of complex parts faster than with conventional methods.

Table 4: Most important patents in the AM area. Source: Own research..

Patent No.	Name	Issued Date	Inventor(s)	Original Assignee	Expiration date	Category
US4247508 A	Molding process	03.12.1986	Ross F. Housholder	Hico Western Products Co..	-	Selective Laser Sintering
US4575330 A	Apparatus for production of three-dimensional objects by stereolithography	11.03.1986	Charles W. Hull	Uvp, Inc.	08.08.2004	Stereolithography
US4863538 A	Method and apparatus for producing parts by selective sintering	05.09.1989	Carl R. Deckard	Board Of Regents, The University Of Texas System	17.10.2006	Selective Laser Sintering
US4929402 A	Method for production of three-dimensional objects by stereolithography	29.05.1990	Charles W. Hull	3D Systems, Inc.	29.05.2007	Stereolithography
US4999143 A	Computer assisted design and manufacture	12.03.1991	Charles W. Hull, Charles W. Lewis	3D Systems, Inc.	18.04.2008	Stereolithography
US5121329 A	Apparatus and method for creating three-dimensional objects	09.06.1992	S. Scott Crump	Stratasys, Inc.	30.10.2009	Fused Deposition Modelling
US5174931 A	Vessel for holding building material, smoothing member for forming uniform coating over previous layer, means to apply pattern of synergistic stimulation to form layer	29.12.1992	Thomas A. Almquist, Borzo Modrek, Paul F. Jacobs, Charles W. Lewis, Mark A. Lewis, Abraham Liran	3D Systems, Inc.	29.09.2009	Stereolithography
US5204055 A	Three-dimensional printing techniques	20.04.1993	Cima, M. ., Sachs, E., Fan, T., Bredt, J., Michaels, S., Khanuja, S., Lauder, A., Lee, S.., Brancazio, D., Curodeau, A., Tuerck, H.	Massachusetts Institute Of Technology	20.04.2010	3D Printing (3DPTM)
US5494618 A	Increasing the useful range of cationic photoinitiators in stereolithography	27.02.1996	Eugene V. Sitzmann, Russell F. Anderson, Darryl K. Barnes	Alliedsignal Inc.	27.06.2014	Stereolithography
US5503785 A	Process of support removal for fused deposition modeling	02.04.1996	S. Scott Crump, James W. Comb, William R. Priedeman, Jr., Robert L. Zinniel	Stratasys, Inc.	02.06.2014	Fused Deposition Modelling
US5529471 A	Additive fabrication apparatus and method	25.06.1996	Behrokh Khoshevis	University Of Southern California	03.02.2015	Fused Deposition Modelling
US5555176 A	Apparatus and method for making three-dimensional articles using bursts of droplets	10.09.1996	Herbert E. Menhennett, Robert B. Brown	Bpm Technology, Inc.	19.10.2014	Fused Deposition Modelling
US5569349 A	Thermal stereolithography	29.10.1996	Thomas A. Almquist, Dennis R. Smalley	3D Systems, Inc.	29.10.2013	Stereolithography
US5572431 A	Apparatus and method for thermal normalization in three-dimensional article manufacturing	05.11.1996	Robert B. Brown, Charles F. Kirschman, Herbert E. Menhennett	Bpm Technology, Inc.	19.10.2014	Fused Deposition Modelling
US5587913 A	Method employing sequential two-dimensional geometry for producing shells for fabrication by a rapid prototyping system	24.12.1996	Steven R. Abrams, James U. Korein, Vijay Srinivasan, Konstantinos Tarabanis	Stratasys, Inc.	24.12.2013	
US5597520 A	Simultaneous multiple layer curing in stereolithography	28.01.1997	Dennis R. Smalley, Thomas J. Vorgitch, Chris R. Manners, Charles W. Hull, Stacie L. VanDorin, Less «	Smalley et al.	28.01.2014	Stereolithography
US5597589 A	Apparatus for producing parts by selective sintering	28.01.1997	Carl R. Deckard	Board Of Regents, The University Of Texas System	28.01.2014	Selective Laser Sintering
US5609812 A	Method of making a three-dimensional object by stereolithography	11.03.1997	Craig M. Childers, Charles W. Hull	3D Systems, Inc.	11.03.2014	Stereolithography
US5609813 A	Method of making a three-dimensional object by stereolithography	11.03.1997	Joseph W. Allison, Dennis R. Smalley, Charles W. Hull, Paul F. Jacobs	3D Systems, Inc.	11.03.2014	Stereolithography
US5610824 A	Rapid and accurate production of stereolithographic parts	11.03.1997	Wayne A. Vinson, Frank F. Little, Wolfgang Schwarzinger, Mark A. Lewis, Yehoram Uziel, Robert T. Pitlak, Stuart T. Spence	3D Systems, Inc.	11.03.2014	Stereolithography
US5637169 A	Method of building three dimensional objects with sheets.	10.06.1997	Charles W. Hull, Paul F. Jacobs, Kris A. Schmidt, Dennis R. Smalley, Wayne A. Vinson	3D Systems, Inc	10.06.2014	
US5639070 A	Method of producing a part from a powder	17.06.1997	Carl R. Deckard	Board Of Regents, The University Of Texas System	17.06.2014	Selective Laser Sintering
US5651934 A	Recoating of stereolithographic layers	29.07.1997	Thomas A. Almquist, Charles W. Hull, Borzo Modrek, Paul F. Jacobs, Charles W. Lewis, Adam L. Cohen, Stuart T. Spence, Hop D. Nguyen	3D Systems, Inc.	29.07.2014	Stereolithography
US5733497 A	Selective laser sintering with composite plastic material	31.03.1998	Kevin P. McAlea, Paul F. Forderhase, Mark E. Ganninger, Frederic W. Kunig, Angelo J. Magistro	Dtm Corporation	20.03.2014	Selective Laser Sintering
US5762856 A	Lamination by solidifying a radiation exposed photopolymer	09.06.1998	Charles W. Hull	Charles W. Hull	09.06.2015	Stereolithography
US6046426 A	Method and system for producing complex-shape objects	04.04.2000	Francisco P. Jeantette, David M. Keicher, Joseph A. Romero, Lee P. Schanwald	Sandia Corporation	08.07.2016	Laser Engineered Net Shaping (LENS)

Ross F. Housholder was the first person to file a patent on a powder-based laser sintering process in 1979. In 1986, Carl R. Deckard filed a patent named “Method and apparatus for producing parts by selective sintering” (Deckard, 1989). This technology enabled the use of materials other than polymers for AM procedures, among them metals and a number of different thermoplastics. Soon after, Deckard and his research team founded the company Nova Automation. In 1989, they renamed Nova Automation to DTM Corporation in reference to the term ‘desktop manufacturing’. In the same year, DTM Corporation started selling the first commercial selective laser sintering (SLS) machines called Mod A and Mod B. In August 2001, DTM Corporation was acquired by 3D Systems (3D Systems, 2001).

Another approach to producing three-dimensional objects from digital files was patented in 1993 by a group of researchers around Michael Cima and Emanuel Sachs of the Massachusetts Institute of Technology (Cima, 1995). Called “3D Printing”, this approach uses a powderized base material that is selectively fused together by jetting a binder into the powder bed. The name alludes to the 3rd dimension that is added to the traditional flat – 2D – printing. MIT licensed 3D Printing to a number of companies for application in various areas such as medical, prototyping and manufacturing. The most widely known spin-off was ZCorporation, short ZCorp, which developed the first full-color 3D printer. In 2012, 3D Systems acquired ZCorp (3D Systems, 2012).

2.2.2 Sketching an emerging landscape of applications

In the beginning, 3D printing technology was mainly used for rapid prototyping processes in engineering-related industries such as aviation and automotive. Since its first appearance around 30 years ago, however, the technology has advanced significantly resulting in a plethora of use cases and applications. Especially the expiration of certain patents that were issued in the 1980ies and 1990ies caused new innovators and companies to enter the 3D printing market with the intention to unleash the technology’s full potential (see table 5). As the technology becomes more efficient and effective, the possibilities for 3D printing become more diverse, dynamic and disruptive. The table below provides a brief historical overview of technological milestones related to 3D printing.

Table 5: 3D printing chronology and milestones. Source: Illustration adapted from Price, 2011.

Year	Event
1991	Stratasys produces the first FDM 3D printer.
1992	The first 3D printer based on stereolithography is produced by 3D Systems.
1992	DTM produces the first selective laser sintering machine
1999	A group of researchers of the Wake Forest Institute for Regenerative Medicine use 3D printing technology to create scaffolds from living cells.
2000	Object geometries produces the first 3D inkjet printer.
2000	Z Corp produces the first multicolor 3D printer.
2001	Solidimension produces the first desktop 3D printer.
2005	Dr Adrian Bowyer founds the RepRap project at the University of Bath based on open-source collaboration.
2006	The first SLS machine becomes viable and opens the door for mass customization.
2008	The RepRap Darwin printer is released as the first self-replicating 3D printer that can produce most of its own components.
2008	Stratasys produces the first biocompatible FDM material.
2008	Shapeways launches the first 3D printing online market place.
2008	MakerBot launches Thingiverse as another file sharing platform.
2008	The first 3D printed prosthetic leg including all relevant joints is produced.
2009	The bioprinting company Organovo produces the first 3D printed blood vessel.
2011	Kor Ecologic unveils the first 3D-printed car called Urbee that consists of a fully 3D printed body.
2011	iMaterialise becomes the first 3D printing service that offers gold and silver as printing materials.
2012	The Dutch company LayerWise produces the first customized 3D-printed prosthetic lower jaw.

2.3 Technology introduction

The following sections provide an overview of different 3D printing technologies to clarify technical terms and to lay the foundation for subsequent elaborations.

2.3.1 From bits to things: The additive manufacturing process

The AM process starts with the development of a digital 3D model or data set containing the complete geometrical information and continues with the transformation of these data into a physical model layer by layer (Hanemann et al., 2006; Huang et al., 2013). Thus, the AM process begins several steps before the print head or laser beam actually kicks into action. The whole process (see fig. 2) is initiated when a user has an abstract image of an object in mind that he intends to 3D print. The next step for him is to find an appropriate software that can model the particular object in digital form in 3D and will provide the 3D printer’s built-in software (also called *firmware*) with the required input data (Lipson & Kurman, 2013). *Computer-aided design (CAD) software* or the scan of an existing artifact can be used to create a 3D model of an object (Campbell, Williams, Ivanova, & Garrett, 2011). Alternatively, the user can search various extensive databases online for a suitable existing design file (e.g. Thingiverse).

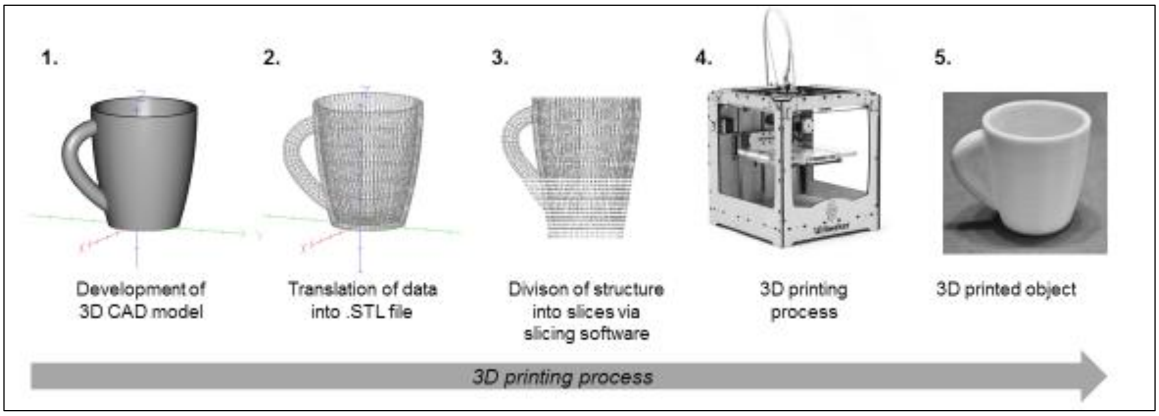

Figure 2: Generalized additive manufacturing process. Source: Own illustration with .stl file taken from http://www.thingiverse.com/thing:24464/#files

Once the design file is ready, the user translates the design file into a special file format called *STL*, which the control software of the printer can read and work with (Lipson & Kurman, 2013). When a design file is converted to STL, the software transforms the entire surface of the digital model into a mesh of connected triangles. When the STL conversion is complete, the volume of the newly wrapped object is completely enclosed by the generated mesh (Lipson & Kurman, 2013, p.79). In the next step, the 3D printer’s firmware reads the data file and slices the model into cross-sectional layers whose spacing depends on the layer thickness of the desired 3D print-process. Then it calculates the required shape of the area that needs to be solidified based on the contour in each layer. When the printer’s firmware has finished this sequence of operations, the actual printing process can start.

2.3.2 Understanding different 3D printing technologies

Various AM procedures have evolved to fulfill requirements of different industries. The following section provides an introduction to the most common AM technologies. The classification at hand is based on Pham & Gault (1998) as well as Gibson, Rosen & Stucker (2010). In the descriptions below, three main categories are distinguished: a) processes that involve a liquid, b) processes that involve discrete particles (powder-based processes), and c) technologies which use a solid.

Class A: Processes involving a liquid

Aa) Solidification of a liquid polymer

The AM processes in this category involve the solidification of a resin via electromagnetic radiation (Pham & Gault, 998, p. 1259). The best known of these techniques is perhaps *stereolithography* (SLA) referring to US Patent #4575330. Thereby, a bath of photosensitive monomer resin solidifies when it is exposed layer by layer to a light source (UV laser). The exposure cures the material selectively, resulting in the final shape of the object. At the beginning, the printer platform is located just below the liquid resin's surface. An optical imaging system consisting of different mirrors allowing a wider laser beam deflection in x, y-direction moves the laser beam along the resin's surface. Where the laser hits the feedstock, it becomes solid. The first slice contour geometry is written into the reactive resin via polymerization. After finishing the first layer, the platform is moved a small distance towards the bottom of the reaction container and the second layer can be written. SLA is particularly suitable in manufacturing for the building of prototypes or master patterns. Furthermore, first models of desktop 3D printers based on SLA have been introduced, such as the Form 1 by Formlabs.

Ab) Solidification of molten material

These technologies describe processes that involve melting and subsequent solidification of the used material, similar to a hot-melt gun. The most popular method is *Fused Deposition Modeling (FDM)* referring to US Patent #5121329. Thereby, a "thermopolymer filament passes through a liquefier heated to a temperature slightly above the melting point of the polymer. A continuous bead, or road, is extruded through a nozzle and deposited on a platform. A different material from a second nozzle is used for support structures, which are later removed by solving or breaking off." (Hanemann et al., 2006, p. 199). As the object is printed "into the air", supporting structures are oftentimes needed for overhanging sections. The expiration of relevant patents in this class triggered innovation activities in the area of home 3D printing and the emergence of a large open-source development community (e.g. RepRap). FDM equipment has a compact size, and the maintenance cost is low. Thus, this technique is widely used in desktop 3D-printers (e.g. MakerBots)

Class B: Processes involving discrete particles

Powder-based processes describe a group of AM methods whereby a solid object is built by fusing powder particles together via a focused laser beam or using a liquid binding agent. After spreading a thin powder layer on the build platform either a thermal beam (laser, electron beam) melts the sections of the powder layer that correspond to the shape of the desired object, or a print head applies a binder on the required areas of the powder thereby solidifying the material selectively. After this step, the build platform is lowered by one layer thickness, a new layer of powder is spread and the process starts again.

Ba) Fusing of particles by laser

Selective Laser Sintering (SLS), referring to US Patent #4863538, uses a high power laser to fuse small particles of the feedstock material (e.g. polymers, metals, ceramics, glass etc.). Hanemann et al. (2006) describe the SLS process as follows:

> […] a thin layer of powder is spread across a platform by a blade or a roller mechanism. A modulated CO_2 laser writes the CAD data selectively on the powder bed so that only the particles in an area with the cross-section of the object are fused by laser energy. To facilitate fusion of the particles the powder bed is heated to just below the melting point of the material. The powder bed is then lowered and a new layer of particles is spread across the building platform. (p. 194f)

With SLS, only the sintered material forms the part while the un-sintered powder serves as a supporting structure. After the printing process, the loose unfused powder can be cleaned away and recycled.

Another emerging AM technology that is likely to gain recognition in the future is *selective laser melting* (SLM). Thereby, complex structures can be generated by using a high-power laser beam to fuse metal powders together.

Bb) Joining of particles with a binder

Three dimensional printing (3DP^{TM}*)*, see US Patent #5204055, is a technique that was originally developed by the MIT and represents a combination of inkjet printing technology and powder sintering. After spreading a thin layer of ceramic, metallic or polymeric powder, a printing head moves across a bed of powder selectively depositing a liquid binding material in the shape of the section. The powder bed, which also acts as a support structure, is lowered and the process is continued with the spreading of a new layer of powder

Class C: Technologies which use a solid

Laminated Object Manufacturing (LOM) is one of the oldest AM technologies in place (Gibon et al, 2010). Thereby, different sheets of material, such as paper, are bonded with a heat-activated adhesive. Afterwards, a laser is used to cut the requested part contour. Another example in that category is called *Solid Foil Polymerisation (SFP)*, whereby sheets of semi-polymerized foils are bonded by curing them with UV light (Pham & Gault, 1277, p. 1278). Since these processes are usually not mentioned in the discourse of 3D printing, they have not been further investigated for the purposes of this report.

Table 6 provides a quick overview of AM processes used in practice. It should not be seen as a comprehensive reference rather than a review of different mechanisms with their main up- and downsides.

Table 6: Overview of AM technologies. Source: Own illustration.

Name	Abbr.	Cls.	Function	Materials	Advantages	Disadvantages
Stereo lithography	STL	Aa	Photo curable, liquid plastic is cured with an UV laser beam exposure.	Liquid, curable plastics, elastomers	smooth/detailed surface	Expensive, printed objects are not thermally stable
Fused Deposition Modeling	FDM	Ab	Wire-shaped plastic is melted and applied on the construction layer by a computer controlled nozzle	ABS, PLA, Wood	Inexpensive	Supporting structures needed, bad surface quality, few materials
Selective laser sintering	SLS	Ba	Powder is applied in layers. Laser sinters particles together.	Metals, thermoplastic	No supporting structures needed, high stability	Not the most accurate process, rough surface
Selective laser melting	SLM	Ba	Using a high-power laser beam to fuse metal powders together	High quality steels, titanium-, aluminum- and nickel-based alloys	Manufacture parts in standard metals with high density	Technology rather slow and (still) expensive
3DP™	Bb	Bb	Printing of a binder onto a powder bed to stick the powder particles together	Starch- and plaster-based powders, ceramics	Works with a wide arrange of material types	Limited mechanical characteristics
Laminated Object Modeling	LOM	C	Flat materials (paper, aluminum) are stacked one by one with glue. Each time, the topmost layer is cut according to the object shape.	Paper, light metals, fiber, glass ceramics	Simple process	Fragile objects

2.3.3 Printing materials and feedstock

The choice of feedstock and scaffolding material is an essential issue when printing 3D objects. Next to the material that is used for building the desired object, some printing technologies additionally require excess material to fill the build tray to capacity. Thereby, the specific type of material that can be processed depends on the additive manufacturing method used.

2.3.3.1 Materials for desktop 3D printers

Today's desktop 3D printers work predominantly with plastic. Vendors offer a large range of different kinds that consumers can chose from based on properties such as color, tensile strength, rigidity, biocompatibility, moisture resistance, and fire retardancy. Generally, the plastic filament used in desktop 3D printers can be divided into two different categories: thermoplastics and thermosetting polymers. The difference is that thermoplastics melt when heated but do not change their internal composition so that they can be melted and re-melted several times. Thermosetting polymers, in contrast, change their internal composition once heated; meaning that they cannot be melted back down into a reusable liquid form (Lipson & Kurman, 2013). A common type of thermoplastic used in personal printers is Acrylonitrile Butadiene Styrene (ABS), the same kind that is also used in LEGO bricks. Another thermoplastic commonly used in personal 3D printers is Poly Lactic Acid (PLA). PLA is a bio-degradable type of plastic that is manufactured out of plant-based resources such as corn starch or sugar cane (Chilson, 2013). This is why it is often referred to as "the green plastic" (Ramon, 2013). Home-scale 3D printers can also work with another category of plastics, soft plastics, called elastomers (Lipson & Kurman, 2013). Just as the name suggests, these rubber-band-like-materials have extensive elastic properties.

To this day, the materials that home-scale 3D printers can work with are largely limited to plastics. One exception are McorTechnology's paper-based 3D printers that use ordinary, affordable office paper as the build material (MCorTechnologies, 2013).

2.3.3.2 Materials for industrial additive manufacturing

In the case of industrial AM, metal is the most commonly used material. Printed metal machine parts are a very popular industrial application for 3D metal printing (Lipson & Kurman, 2013). The variety of metals that can be 3D printed is huge and still growing: Tool steels, stainless steels, titanium, titanium alloy, aluminum casting alloys, nickel-based alloys, gold, and silver all constitute metals that today are used in industrial additive manufacturing processes.

Glass, one of the most common materials used by humans, has been one of the slowest materials to gain traction in the 3D printing area. Glass is hydrophobic, meaning that it repels water and, hence, does not adhere very well (Lipson & Kurman, 2013). On top, powdered glass is unpredictable when exposed to heat. Two students from the University of Washington managed to print objects made of recycled glass in the research lab. However, commercial application of glass printing is still predominately for art and jewelry (Lipson & Kurman, 2013).

One trend in material development is furthermore the emergence of *digital materials*. Digital materials are composite substances made by jetting two different materials simultaneously. The resulting materials can simulate a wide range of advanced material properties including toughness and temperature resistance of engineering plastics.

3. Areas of application: Trends and Case Studies

3.1 Additive manufacturing for industrial production

This section explains how 3D printing can be applied in industrial production. The chapter is structured into three parts. First, the status quo and current trends of industrial AM are described. Second, four case studies are presented, covering four different industries and four different objectives reached by using this technology. The third part consolidates the findings and draws the reader's attention to future opportunities and related challenges in the context of industrial 3D printing.

3.1.1 Status quo and trends

There are two general trends that are likely to shape the future of additive manufacturing. These include the transition from rapid prototyping to rapid manufacturing and the possibility to enable mass customization of end-products.

3.1.1.1 Transition from rapid prototyping to rapid manufacturing

On an industry level, additive manufacturing (AM) processes have been around for decades. The first forms of quickly fabricating a scale model were already available in the 1980s (Bird, 2012). The introduction of *layer manufacturing* (LM) was the first AM process and laid the foundation of today's *rapid prototyping* (RT) (Levy & Schindel, 2003). As the name implies, the first use cases for the required machines were producing models and prototype parts. With improving properties and new AM techniques coming up in the past 15 years, it became plausible to take this approach to the next level. Around the turn of the millennium, first researches proposed the LM technology for *rapid tooling* (RT) and *rapid manufacturing* (RM) (Levy & Schindel, 2003). Using RP processes to produce long-term usable components defined a new area of manufacturing. In 2011, the Economist points out the possible disruption potential of AM:

> Just as nobody could have predicted the impact of the steam engine in 1750 – or the printing press in 1450, or the transistor in 1950 – it is impossible to foresee the long-term impact of 3D Printing. But the technology is coming, and it is likely to disrupt every field it touches. (The Economist, 2011)

However, the true disruptive character of AM is not yet present in rapid prototyping, but will appear within the transition to rapid manufacturing. AM could then undermine economies of scale, which once turned the classical manufacturing process upside-down. Where mass production shows the hyperbolic curve with decreasing costs per unit with increasing scale, AM presents an almost linear characteristic. In addition, increased complexity comes along with no significant increase in production costs (Eisenhut & Langefeld, 2013). Generally speaking, the more complex the product and the lower the lot size, the better are the conditions for a successful and cost-efficient application of RM.

RP as the initial step in this evolution focused on the key fact of being able to produce a 3D prototype in a very short time. The models, mostly consisting of polymer, were a proof of concept enabling designers to quickly iterate and delivering a huge amount of new possibilities. With the move to RT, however, the future major importance of the material properties became clear. In addition to being “printable”, new conditions (e.g. melting point, stability, etc.) had to be met. RT generally tries to deliver long-term consistency tools to form several thousands of parts (Levy & Schindel, 2003). In addition, AM introduces new geometries, exceeding former limitations, which offer new possibilities to create highly complex structures. Thus, even conventional casting processes are reaching a new level of complexity due to printed one-time molds. Finally, RM is considered the supreme discipline of AM. The materials of the final product have to be highly durable and meet all the requirements of a conventionally produced product, which is still one of the major challenges in RM.

Only if these hurdles are overcome, RM can display its true potential: First, the increase in product development speed enables a faster time to market. Second, RM provides more complexity for no additional cost. As aforementioned, it enables new degrees of freedom in product design and allows developers to make use of more complex structures. This means either that the same properties of a product can be achieved with less material and reduced weight due to former impossible, additively manufactured geometries, or that the same amount of material can be used in AM to create advanced structures to enhance performance. Exhibit 1 explains the new freedoms in product design due to AM in more detail. However, the limited build rate of RM compared to classical mass production defines a major hurdle. Experts think that this limiting factor will hinder a disruption in certain fields through RM (Eisenhut & Langefeld, 2013; Wohlers & Caffrey, 2013). In addition, most of the time for additively manufactured end-products, a finishing process is required in order to create a similar haptic.

The transition of RP to RM has already begun in some industries. The best example is the medical and dental industry (see chapter 3.2), which considers RM already state-of-the-art. Dental bridges and hearing aids are mostly build additively since this enables a high degree of personalization. Another leading industry in the field of RM is aerospace. The production of lightweight parts is a major field of interest. The number of products produced by AM and currently used in military aircrafts is considered to be a 5-digit number (Honsel, 2011). The latter case is elaborated in detail in chapter 3.1.2.2.

Notwithstanding striking examples, not everyone sees the transition from RP to RT to RM as clear and inevitable. There are many companies focusing only on one sector, although they know about the competitive market and the increase in dependency by staying in a single area. Especially for companies in the fields of printing polymer and sand still focus on RP and RT in their business. Finally, AM is still extremely limited to certain use cases due to the materials. For RM, metal printing technologies are the clear driver (Interview 2, 2014). With more sophisticated methods, firms like EOS have already started the age of RM. This production approach is considered a game changer since design will become rather function- than production-driven (Eyers & Dotchev, 2010).

Currently, the market is still relatively small with €1.7 billion, but is expected to grow to €7.7 billion in 2023. The reason for this sharp increase lies in general adoption but also in expected massive technical improvement. On the one hand, the build rate is predicted to increase by a factor of eight until 2023 and on the other hand, powder manufactures will be able to cut the price to a third due to enhanced production technology and logistics. These effects will be the key drivers of RM to become increasingly important in the world of production. Although RM will have a major impact in small lot size industries and for mass customization, it is unlikely that all existing ways of manufacturing are being disrupted (Eisenhut & Langefeld, 2013).

New degrees of freedom in product and process design

AM offers several new degrees of freedom in the design of products and production processes. The additive nature of 3D Printing processes means that products with complex inner structures can be printed at no additional cost (Eisenhut & Langefeld, 2013). This opens the field for many kinds of approaches to use these more diverse structures.

1. Opening up the design spectrum

In every production process, compromises have to be made between the preferred design of a piece and the constraints of the manufacturing process. For instance, in injection molding, one has to design the part in such a way that mold pieces and produced parts can be separated after the molding process. AM has different design constraints than traditional manufacturing processes. Thus, it can (sometimes) provide a way of production that requires fewer compromises than traditional manufacturing techniques (see chapter 3.1.2.1).

2. Enabling material savings and weight reduction

AM offers the possibility to achieve the same properties of a product with less material and reduced weight due to former impossible, additively manufactured geometries. A good example are biomimicry designs, such as lattice structures, that can hardly be produced with traditional manufacturing techniques. Parts that use these structures, however, can feature both a higher stability and a significant reduction in weight.

2. Reducing assembly efforts in part production

AM is capable of reducing the assembly efforts in parts production. Oftentimes, a product that has to be manufactured in parts and assembled later can be consolidated into fewer parts with higher complexity. Following the same idea, certain functionalities might be directly printed into the part. For instance, two parts that are connected by a joint might be directly printed in one piece (Gibson, Rosen, & Stucker, 2010). The fact that 3D printers do not use different tools for different pieces means that changes in product design can be directly transferred to the manufacturing process without the need to adapt molds for casting or other tools (Gibson et al., 2010). Furthermore, different pieces can be printed in any order, and the product that a 3D printer produces can easily be changed by simply swapping out the CAD file. This makes 3D printing an enabler of mass-customization, since every piece that is printed can be differing from the piece before at no additional costs (see chapter 3.1.2.4).

Exhibit 1: New degrees of freedom in product and process design. Source: Own research.

3.1.1.2 AM as an enabler of mass customization

Along with the trend to use AM not only as a mean of RP and RT but also as a part of manufacturing processes, the question arises what opportunities the adoption of RM offers for industrial players.

Using AM offers several advantages over established mass production processes. First and foremost, changes in product design can be directly transferred to the manufacturing process without the need to adapt molds for casting or other tools (Gibson et al., 2010). Second, parts can be manufactured in any order on an AM machine. Third, the product an AM machine is currently producing can easily be changed by simply swapping the CAD file. In sum, AM makes many design constraints irrelevant that are prevalent in established mass production processes.

This in turn has several implications for manufacturers: First of all, manufacturers can now mass produce products that are adapted to their individual customers' needs – if an AM system is used to manufacture a part – a change in the design of this part does not create additional cost. Secondly, companies can integrate their customers into the product development process more easily. Companies might offer their customers simple design tools to express their preferences, which can then be directly incorporated into the manufacturing process and end in a customized product built to the user's specifications. Nikolaus Franke and Frank Piller executed a study where they examined the impact of this so-called customer co-creation on the customers' perception of the product value. They found that customers valued products they contributed to much higher than their non-customized counterparts (Franke & Piller, 2004). Thus, mass customization allows companies to differentiate themselves from their competitors and to take a price premium, both by better suiting their customers' needs.

Although some examples of companies enabling their customers to customize their product already exist today without AM – for instance the customizability of premium cars on the websites of the manufacturers – AM can simplify the processes of the manufacturer tremendously (see also chapter 3.1.2.4). As an example, product customization without AM is often achieved by modularity and postponement. This means producing different variants of parts to customize by different part selection and postponing the actual customization as far into the product manufacturing process as possible (Wong & Eyers, 2010). Modularity and postponement, however, come with a high cost, while mass customization on an AM machine is free of additional cost.

However, AM can only solve problems coming from mass customization that are technology-related. Therefore, it is important to identify what aspect of a product should be customizable and support the customer in the customization process itself (Salvador, De Holan et al. 2009). Problems arise for instance when presenting the customer with too many choices or a too complex mean of participating in the product development process (Desmeules 2002). It is crucial to simplify the interface for the customer as far as possible, as too much choice, freedom or complexity in the customization process can lead to customers postponing their buying decisions or losing interest completely (Salvador, De Holan et al. 2009). In sum, AM is an enabler of mass customization on the production processes side, but it is not an overall solution for the challenges that mass customization raises.

3.1.2 Case Studies

This chapter of the report shows how versatile the application of AM in the industry can be. Overall, four case studies are presented, covering four different industries and four different objectives reached by using this technology. The topics were chosen in order to reflect the trends which were either initiated or significantly accelerated by AM and which are likely to emerge in other industries as well. All case studies serve as examples for the aforementioned status quo and elaborate on current applications of AM. The first case study presents the potential of AM to produce complex parts based on the example of the tooling industry. The second case study deals with the aerospace industry, in which AM can be used to reduce the weight of components, which leads to significant fuel savings. The fourth case study deals with the car industry, in which the application of AM could decrease the assembly costs. The fourth case study finally shows that AM can also be used as an enabler of customization and possibly even mass customization in the footwear industry.

3.1.2.1 Additive manufacturing of injection molding dies

Injection molding has become the most commonly used manufacturing process for the automated production of plastic moldings. By applying this process, plastic parts with complex geometries can be produced cost-efficiently and fast while requiring none or just a small amount of post-processing. As regards the process as such, plastic granulate is heated in a screw cylinder and afterwards forced into a mold cavity using high pressure. After a cooling phase, the two molding halves open up and the part is extracted automatically (Bonnet, 2009).

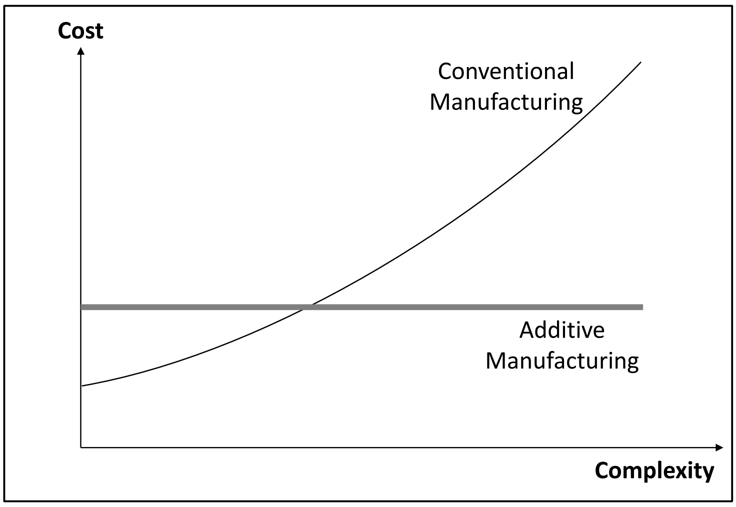

Figure 3: Correlation between production costs and complexity of parts. Source: Eisenhut & Langefeld, 2013

Traditionally, molding dies – which define the mold cavity and the geometry of the finished part – are manufactured from a solid metal block using machining operations. Figure 3 compares the correlation between geometric complexity of the produced parts and production costs for conventional manufacturing processes and AM. One can see that the production costs for AM are essentially independent from the complexity of the part. In contrast to that, a strong progressive correlation exists for conventional manufacturing. Applied to the case of molding dies, this progressive correlation means that the costs of producing a die follows an asymptotic characteristic and becomes infinite at a certain point. At this point, the die cannot be produced using machining operations due to restrictions from the manufacturing process (Dimla et al., 2005). Many of these restrictions do not apply for AM. Thereby, the freedom with regard to the geometric shape of molding dies becomes higher.

A critical parameter in the injection molding process is the cooling of the molds. The proper discharge of thermal energy is crucial when a high production rate and high part quality have to be achieved (Sachs et al., 2000). The cooling stage accounts for approximately 70-80% of the cycle time during the injection molding process and is thereby highly relevant for the productivity of the process (Shayfull et al., 2014). In this regard, the application of AM methods allows for the fabrication of complex cooling passages inside the molding die, referred to as conformal cooling channels. These cooling channels cannot be produced by traditional drilling methods. A visualization of a geometry with conventional and conformal cooling channels can be seen in figure 4. The improved cooling opportunities due to AM result in cycle reductions between 10% and 30% (Radig, 2011; Concept Laser 2014).

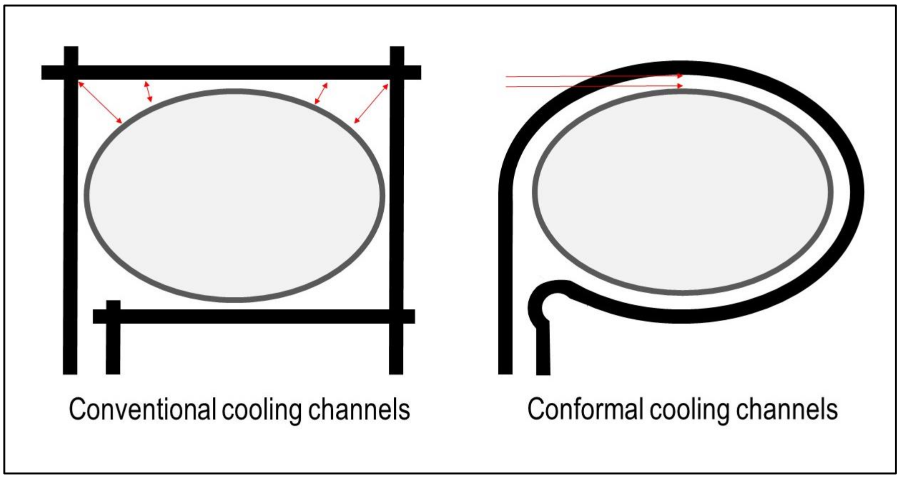

Figure 4: Conventional cooling vs. conformal cooling. Source: Own illustration adapted from http://www.innomia.cz/en/services/conformal-cooling

Besides a reduction in cycle times, the quality of the produced parts can be improved by conformal cooling. Due to the equalized temperature distribution across the part, the shrinkage occurring outside of the form after extraction is uniform and thereby avoids post-injection warpage and supports higher accuracy of the part geometry. Besides the higher accuracy, the conformal cooling channels allow for an increased surface quality of the produced parts, eliminating the need for post-processing on visible parts (Dimla et al., 2005; Radig, 2011).

AM of molding dies including the implementation of conformal cooling channels is already highly used in the tooling industry (Eisenhut & Langefeld, 2013). This is due to the fast amortization of the higher production costs of AM through the reduced costs from shorter cycle times and less post-processing (EOS, 2013a). Current research is focusing on the further improvement of conformal cooling channel design by automating the process of the design (Au et al. 2011; Wang et al., 2011).

The described developments implicate a major change in the way injection molding dies will be manufactured in the future. Especially for contract manufacturers, this means the need to invest in SLS or SLM machines, rather than CNC milling machines.

3.1.2.2 Additive manufacturing in the aerospace industry

In the aerospace and aviation industry saving weight is one of the major objectives. (interview 3, 2014). Prototyping of different components has always been the key to develop new light-weight products, which is why RP found its way relatively early into this industry. According to interviewee 3, the Airbus Group began experimenting with AM technology already in 1993. Since weight saving aspects were promising due to the use of novel structures, the company decided to investigate this trend in detail. Since 2003, Airbus finally uses AM and still considers the technology to have a large potential in the aerospace sector (interview 3, 2014).

There are two main reason why the aerospace industry is one of the pioneers regarding the integration of AM technology. First, the relatively small number of some hundreds to a few thousand parts makes design efforts in single parts for aeronautic industries interesting (interview 3, 2014). Second, the lot sizes in aviation are comparably small and the parts show a certain complexity.

Furthermore, since the production of final metal parts became reality, one can think about many different applications of AM in the aviation industry. Especially because of the long utilization of an aircraft, permanent weight reduction is elementary to safe costs. Over a lifetime, every saved kilogram of weight equals a reduction in fuel consumption of 45.000 liters of kerosene, or around € 27.250 (Ayre, 2013). Although this would be highly interesting for commercial aerospace industry, AM is primary used in military applications so far. The manufacturer "Manufacturing on Demand" states that over 20.000 of their parts are already used – with the majority in military airplanes (Honsel, 2011).

The most valuable asset for enabling weight savings is the usage of complex shaping and integration to enable bionic design. Bionic design transfers structures found in nature into an engineering context. For instance, comparing the composition of a bone with a prosthesis in medicine, they usually are of a different internal architecture. In contrast to artificially produced forms, objects in nature build a net shaped interior, leaving spaces between supporting structures. This saves a lot of weight while maintaining a high stability. Being able to design components based on this logic and exactly according to their load requirements is a major advantage of AM and will lead to weight savings of 35-70% (interview 3, 2014).

There are many examples that already show how a bionic and complex design can save a significant amount of weight. The SAVING project, for instance, presented its improved design of an additively manufactured titanium belt buckle for airplanes. The weight from the original 155g heavy steel buckle could be reduced to 70g, which represents a reduction of 55%. Installing these buckles in an A380 with only economy seating (853 seats), this results in a reduction of 72.5 kg. Taking the before mentioned savings per kilogram into account, this equals fuel worth approximately € 2.0 million (Ayre, 2013). In addition, EOS GmbH released a case study of a topology optimized Airbus A380 bracket made of stainless steel powder, produced with the DMLS technology. In comparison to conventionally manufactured parts, the weight could be reduced by 40% from 56g to 33g (EOS GmbH, 2014b).

Furthermore, there is the possibility of producing parts with improved capabilities. This could be either a result of revolutionary new components or a reduction of losses due to one part with integral components. EOS GmbH was able to optimize a jet engine by following both approaches. By building the part bottom-up by laser sintering a cobalt-chrome alloy, they were able to improve the fuel efficiency by optimizing the airflow and fuel swirling in the part. Redesigned turbines as well as lighter and more precise fuel nozzles enabled this advancement. In addition, they enabled new forms of cooling by integrated fuel channels. This resulted in a 50% cost reduction on top of the additional 40% reduction in weight, while simultaneously increasing robustness since no joint sections were necessary any more (EOS GmbH, 2014a).

Finally, AM offers also possibilities of waste reduction and emissions in the aerospace industry. Many of the conventionally casted and subsequently milled parts are built top-down and produce a lot of undesired waste. A combined study of EADS and EOS shows that the buy-to-fly, i.e. the ratio between how much material needs to be purchased in order to manufacture the component and the flying part, can be reduced from 2.1 to 1.5 or by 29% (EOS GmbH, 2013c). The study shows further that the emissions of carbon dioxide through the static phases can be decreased significantly.

For the future, AM is predicted to gain even more relevance in the aerospace industry. Airbus just recently announced their plans on producing bigger parts of their aircrafts with AM. For instance, they joined a cooperation with the Chinese Northwestern Polytechnical University to experiment with printing fuselage parts (Odrich, 2014). According to interviewee 3, calling 3D printing “the next industrial revolution” is going a little too far, although it could be valid for industries like aeronautics. The assertiveness of 3D printing will still depend on the final cost of individual parts. Nevertheless, the interviewee considers this technology an important movement, which could be a game changer for some industries already in the next 3 to 5 years.

3.1.2.3 Additive manufacturing in the car industry

Most modern car manufacturers offer an increasing variety of different car models that are customizable by the consumers. Despite systems like the modular transverse/longitudinal matrix used at the Volkswagen Group, which allows sharing even essential car parts among different models and brands, many components still require model-specific production. This affects particularly interior features which simultaneously present the highest customization potential in a car. The large number of different components creates a considerable overhead during production. Here, AM could provide a novel approach in producing the desired customer-customized parts en bloc and reduce assembly costs. While already being practiced in the premium car segment – where for instance Bugatti is "printing" complete dashboards – AM has not yet arrived in the mass-market production.

In the following, different aspects of printing car components in the industrial mass production environment are illuminated. There are several benefits for assembly from using 3D printers: Firstly, the size of the single car components can be significantly bigger since 3D printers can manufacture more complex structures – as previously mentioned. The American company KOR

Ecologic has applied such an approach. Their car called Urbee is mainly produced by using 3D printers. In total, Urbee consists only of 50 single components (Bargmann, 2013; Maxey, 2013; George 2013; Spiegel Online, 2013). Compared to a standard car with over 10,000 parts, this is dramatic simplification in the assembly process (Süddeutsche Zeitung, 2010). Currently, Urbee is mainly build out of ABS, printed with FDM machines. The entire car is around three meters in length and weights around 544 kg. The printing process is outsourced to Redeye, an on demand 3D printing service provider, and it takes around 2500 hours to finish a single car. The German company EDAG has a similar goal. At the Geneva Auto Show (Maxey, 2014), they presented a new automotive design in an organic shape. The car body is entirely manufactured with high-resolution FDM machines out of carbon. Again, since the car body is made out of only a few single parts, it is much simpler in the assembly process. In the far future, AM could provide more ways to automate the production. Car parts could be directly printed at their place in the car. Taking this to an extreme, one can even imagine complex parts like engines being printed in bloc directly into the engine compartment. Hereby, the engine would not only get more efficient and less prone to error, but also easier to assemble.

Additionally, AM could render spare part inventories obsolete. Currently, manufacturers are required to lead inventories of spare parts – for current products and for legacy products. This causes significant costs. On the one hand, spare parts have to be produced upfront since the tools for their production might not be available for the whole lifetime of the product and in order to guarantee timely delivery. On the other hand, the inventories have to be rented and maintained. AM can enable manufacturers to only keep the CAD files of the parts and then manufacture the spare parts on the customer's demand. Thus, only the raw materials have to be kept in stock. In this way, AM might enable a large cost-saving potential by eliminating the need for spare part inventories.

According to interviewee 6, this is not very likely to happen in the next decade (interview 6, 2014). Although using AM in the automotive industry offers a lot of benefits, there are still a lot of technical challenges to overcome during the next couple of years. State of the art AM still cannot compete with the speed and efficiency of conventional production technologies like machine presses, lathing machines, or traditional mills.

3.1.2.4 Additive manufacturing in the footwear industry

Every individual has a slightly different walking style and shape of feet (Grossman, 2011), which means that there is a relatively high potential for shoe customization. This idea is supported by the fact that wearing wrong shoes may lead to back pain, foot problems like corns or callus, or even foot ulceration (Wesley et al., 2007). However, by today, the footwear industry does not reflect this fact sufficiently and rather seeks economies of scale through highly standardized production processes.

Until recently, AM was used mainly for prototyping purposes in the footwear industry. However, established market players as well as emerging startups have started investing time and money in AM technology in the last few years. In February 2013, one of the most prominent shoe producers, sportswear company Nike, released football cleats which contain the so called "V Plate". This is a 3D printed nylon basis which together with other elements increase their speed (Stinson, 2014).

Another example is the American footwear producer New Balance, who focuses on creating customized shoes for professional runners. First, they let the athlete wear a pair of shoes equipped with sensors and use a motion-capture system to observe how athlete's foot behaves inside the shoe under simulated race conditions. The data is then gathered and used to 3D print a plate for track spikes which is attached to a standard upper (Fitzgerald, 2013). The company aims at offering customized spike plates and midsoles to competitive runners within five years, and then to a broader audience based on a price premium. According to Katherine Petrecca, manager of studio innovation for New Balance, the price of these products will be high until the demand increases and the 3D printing technology improves (Luna, 2013).

Besides multinational corporations, customization through AM is also a topic for several startups. One example is the New Zealand-based company Three Over Seven which plans to produce sockless, woolen shoes equipped with a 3D printed sole based on scans of their customers' feet (3Ders, 2014b). Another example is company SOLS which raised US-$ 6.4 million in Series A funding after obtaining US-$ 1.75 million in seed funding for creating individualized insoles. Its customers can record a video of their feet with a special App, based on which the company produce the insoles. SOLS is currently working together with 50 doctors in the USA who are prescribing these insoles to the patients and is planning to significantly scale its operations until the end of 2014 (Perez, 2014).

As demonstrated on the examples above, there is a certain trend towards the use of AM in the footwear industry and that customization starts to become a relevant topic for some companies. The question is whether and in which direction this trend will develop. According to interviewee 4, it is likely that AM will enable mass customization in the footwear industry (interview 4, 2014). In one of his visions of the future, the foot of customers and their walking behavior will be analyzed immediately after entering a shoe store. At the check-out desk they would simply choose the type of the shoe, some additional specifications and wait for a few minutes for the shoe to be customized using a 3D printer directly on spot (interview 4, 2014).

Although mass customization is traditionally believed to incur additional costs for the producer (Gilmore & Pine, 1997), and, as explained in other chapters of this report, the integration of AM into a large-scale production may be difficult, there are still incentives for producers to select this way. Firstly, consumers are likely to pay a premium for customized products (Weller et al., n.a.). Secondly, the use of AM is likely to decrease the costs of mass customization significantly. Finally, the amount of overproduction can be reduced by on-demand production enabled by this technology. According to interviewee 4, there are a few examples in which one third of the overall shoe production does not find a buyer and has to be destroyed. Therefore, mass customization of shoes may be beneficial for the producers even if it incurs higher costs per finished product than in case of standardized production.

Since increased production costs are not necessarily the most critical problem, the vision sketched above is mainly hindered by the current state of technology. However, if the technology improves and the vision comes true, the whole supply chain of the footwear industry could be disrupted. Several steps of the production process would be insourced back to point of sale. Taken to the extreme, this might have severe implications for low-cost countries from which the majority of shoes are exported today. The outsourced production of finished goods would have to change to the outsourced production of incomplex basic components, which cannot be customized. Consequently, the production of individualized parts and final assembly would take place first at a shoe store, or another place relatively closer to the customer, such as a decentralized manufacturing hub – a so-called corner factory (interview 4, 2014).

Whether or not this vision comes true, AM is likely to play an important role in the footwear industry in the future and shoe producers will have to adapt this technology at least to some extent. Therefore, it is possible to expect that intellectual property in this area will become an important asset in the next few years. This conclusion is also supported by the fact that some companies are already applying for patents related to 3D printed shoes, which might give them a significant competitive advantage in the future (Krassenstein, 2014b).

3.1.3 Outlook: Possible changes in production processes

The potential of AM can be estimated based on various benefits for the manufacturing industry, especially in the automotive and the aviation industry. The case studies have shown that AM is particularly valuable because it reduces lead time significantly, as even complex objects can be manufactured in one process step (Eisenhut & Langefeld, 2013). In many cases, there is no need to assemble different objects to one single component or, at least, assembly requirements can be notably reduced. Even for some very complex parts it is possible to print them in one piece (Eisenhut & Langefeld, 2013). The same accounts for tooling. AM allows direct production and thus helps to save costly and time-consuming tooling methods, as single items can be produced inexpensively without incurring the mold and tooling costs of traditional manufacturing (Grynol, 2013). Thus, AM does not only facilitate time savings and logistics by skipping steps in the production process, but it also implies a shorter time-to-market (Lindemann et al., 2012).

Rapid technologies are particularly valuable in the production of components with complex geometries with any kind of shape such as internal passageways, undercuts and other features that are difficult or even impossible to manufacture with conventional techniques (Bogue, 2013). As mentioned in chapter 3.1.2.2, one of the industries already exploiting this potential is the aviation industry (Eisenhut & Langefeld, 2013). There, AM technologies enable savings in weight up to 70% of the original part weight due to the ability to manufacture complex geometries in the components, which translate to massive fuel reduction and thus cost savings during flights (Lindemann et al., 2012).

In conventional manufacturing the direct connection between complexity of the product's geometry and manufacturing costs is a known restriction. By using AM this relationship does not exist anymore due to the elimination of costly production tooling (Lindemann et al., 2012;

Eisenhut & Langefeld, 2013). The geometry of an item can be changed by one person with the help of CAD-software and the 3D printer produces the new item. There is no need of the cost- and time-intensive manufacturing. New machines, tools and even small series can thus be produced at a very low price compared to conventional manufacturing. This opens up new possibilities in the area of mass customization. Small changes to the original product can be done in a comparably short time and very specific to the need of the customer. The "footwear case" in this report (chapter 3.1.2.4) shows the strength of this benefit in detail. Also, in the medical area, the strength of mass customization is exploited already to a large extent in the production of tooth implants or hearing aids. Other areas where mass customization shows high potential, are industries where already today customers pay a high price for personalization, like the automotive industry. With virtually no additional costs stylistic elements personalized to the car owner can be offered, while exploiting a considerable higher willingness-to-pay of the customer enabled by personalization (interview 17, 2014).

As a matter of fact, AM is still a very young production method and its usage is associated with several drawbacks. For example, even though the variety of materials for AM is growing, the amount to choose from is still limited, and the printed quality, which typically requires post-processing, is in some cases inferior to those produced by conventional manufacturing methods. Furthermore, producing pieces with AM technologies with certain materials can be more expensive than using conventional technologies. For example, materials like titanium are still very expensive and can raise costs up to nearly 50% even for low volume parts (Lindemann et al., 2012). In addition, the ability of printing with two different materials within the same item is not advanced yet. Depending on the kind of AM technology, a lot of resources are often wasted in the production process. This is especially problematic in the case of technologies that involve sand. Furthermore, for most 3D printers the production of extremely large items like pipelines is not possible, as they are restricted by their chamber size. In these cases traditional production methods are still preferred (Eisenhut & Langefeld, 2013; Grynol, 2013). Depending on the kind of product, 3D Printing technologies can be very slow when it comes to large volumes of items. Because of these slow build rates and a discontinuous production process, AM cannot reach economies of scale as easily as traditional manufacturing methods and this can raise the overall production costs (Eisenhut & Langefeld, 2013; Grynol, 2013).

At the moment, AM affects only a very small part of the manufacturing industry. However, with increasing fabrication speed and progress concerning material and design of the technology, it becomes likely that AM will be applied in mass production. This drives the future vision of „Corner Factories" – numerous locations in short distance, where customers can send their CAD data and can pick up the 3D printed and finished product. Campell et al. (2012) share this vision as they say if fabrication speed was significantly increased, parts would become available in minutes rather than hours. Consumers would be prepared to wait for this short time period for their parts to be made over the counter. These machines were likely to be seen in shopping malls and other locations where consumer parts can be made to order (Campbell et al., 2012).

Another relevant development is the expiration of several patents on AM technologies in the industry. Once protected technologies are made available to a wide amount of companies, acceleration of innovation and adoption of these technologies in different industries will follow. It is expected that medium cost AM equipment will be developed in the next ten years as the primary patents expire, and that these devices would foster increased feedstock demand which in turn would accelerate entry of major suppliers into the marketplace with their new and improved materials (Campbell, Bourell et al. 2012). This way, competition will increase in the market, which in turn will drive down costs of AM technologies and eventually also costs for consumers.

The advancement of AM technologies might also bring changes in working modes of manufacturing facilities from a labor perspective: First of all, a broad application of AM might drive down labor costs, especially as post-processing becomes more automated and the excess-powder will not have to be removed manually anymore. While the production process of AM itself is nearly labor-free, the post processing is not yet automated (Lindemann et al., 2012). As the post-processing of additive manufactured items represents a big share of the overall AM labor costs, there is a potential for savings in the future. The technologies are also expected to become much more reliable, which will result in less time and costs concerning monitoring and troubleshooting the systems (Eisenhut & Langefeld, 2013). Finally, with the optimization of the powder dispensing process and the chamber- and laser-system, build rates will increase significantly (Eisenhut & Langefeld, 2013).

However, until AM technologies can become mainstream, many hurdles besides technological ones related to the 3D printers as such, have to be overcome. First, not only AM technologies have to advance, also the CAD software to design parts. So far, the available CAD-software is not capable of capturing the full spectrum of what will be possible with AM in the future. Examples are the ability to represent several materials or colors in the same model, the ability to have a gradual change from one material to another, the ability to assign a particular surface texture or pattern to a part and the ability to generate and represent complex internal structures (Campbell et al., 2012). These issues are worked on and a newly released AMF format seems promising in addressing these difficulties at least partly and thus will most likely replace the former format STL.

Second, Campbell et al. (2012) and Gausemeier et al. (2012) suggest that to unleash the full potential of AM, there needs to be a disruption in the education sector. Not only do designers need to forget their design limitations, which they were taught in school and start to think the without restrictions. For AM to reach its full potential, the strict separation of both areas in education needs to dissolve to form people that are able to design a functional but also aesthetic product. The current educational system tends to produce designers who are capable of either one or the other. AM, on the other hand is uniquely capable of producing something, which is both without the need for compromise. That is why "hybrid" designers are needed who are capable of taking inspiration for their concepts from nature, fashion or the built environment and then converting these into product forms that will also perform efficiently and ergonomically (Campbell et al., 2012). This implies that at universities AM needs to be included in design course curricula, to get trained creative minds into industry manufacturing processes. It could be argued that the ultimate limitation to the shapes created by AM will be the imagination of the designer (Campbell et al., 2012). The relevance of education was also emphasized by interviewee 4, who sees it as one of the most important corner stones of a successful implementation of AM. He stresses out that the benefits of this technology can be harvested only by those who understand it and who can design for it. In his opinion, it is also important to keep in mind that AM is not going to replace conventional manufacturing, but rather enable the creation of entirely new products or improvements of existing ones.

Third, in May 2013, first discussions started, if AM technology opens up critical opportunities for uncontrollable misuse and terrorism. The trigger of this public discussion was a 3D printed handgun that slipped the airport security in the United States and the owner could take it to the aircraft undetected. The file for producing the weapon was designed by anti-government activists and was freely available on the internet, ready to be printed by an inexpensive US-$ 8.000 3D printer. The 0.38 caliber liberator comprised 15 printable plastic components and a single metal part which acted as the firing pin and which appears to be too small to trigger metal detection systems. The plans for the pistol were downloaded 100,000 times before the files were removed at the request of the US Department of Homeland Security (Bogue, 2013). The story made the headlines and many people heard of 3D printing for the very first time. Even though experts said that the weapon was not ready to shoot and without being able to print explosives or gunpowder this was just a trick to scare people, it still sticks in people’s minds. Incidents like that might hinder the adoption of AM due to an irrational fear of a technology that has not unleashed its potential yet (Bogue 2013).

Finally, other hurdles that keep many firms to adopt AM technologies are admissions and lengthy certification procedures as well as issues of intellectual property. These topics, however, are elaborated in detail in chapter 4.4.

3.2 3D Printing in the healthcare and well-being sector

In recent years, 3D printing technology has gained momentum in the healthcare sector by providing a plethora of new solutions in the areas of surgical guides, medical manufacturing and bioengineering. Especially the technology's potential to produce individualized solutions in cost- and time-efficient ways as well as constantly rising demand of quick medical solutions makes 3D printing particularly interesting for medical applications. Next to 3D printing for medical applications, there is also a discussion whether and to which extent 3D printing can be used for artificial food production. In this area, especially the US National Aeronautics and Space Administration (NASA) has received public recognition for granting US-$ 125.000 to a research institute to create a first prototype of a universal food synthesizer (Kaiser, 2013). The motivation of NASA was to come up with a new way to ensure food supply in space.

3.2.1 Medical applications

3.2.1.1 Medical manufacturing

Preparation of complex medical procedures

3D printing technology can be used for the preparation of surgeries and the production of surgical guides to improve the precision and success ratio of complex medical procedures, such as the insertion of implants and transplants (interview 8, 2014). Thereby, 3D printing technology and the combination of relevant software and hardware may support surgeons in two ways:

(1) Development of 3D printed anatomic replicas based on individual patient data. These models can provide surgeons with a precise picture of a patient's anatomy, which ensures a better planning of the procedure. Furthermore, surgeons have the possibility to practice the upcoming procedures on the printed models (The Verge, 2014).

(2) Production of surgical guides, i.e. "surgical instruments that fit the unique shape of the patient's bone and guide the surgeon's drill and sawblade to the exact position and direction defined in the surgical plan" (Park, 2013). These surgical guides can be used to test implants regarding size and fit before the actual surgery. In this way, patients-specific adaptations can be made in advance, such as "re-bending of titanium implant plates to the patient's exact specifications and preoperative investigations across maxillofacial, orthopedics, neurology, spinal and ears, nose and throat wards, to identify the correct procedure and improve outcome" (Rockman, 2014).

For the preparation of 3D printed anatomic replicas and surgical guides, visual information in form of standard DICOM files, which are generated during medical examinations, are used as a data basis. These files are then converted into virtual 3D models and file formats. Afterwards, the model can be printed according to the demands of the respective procedure.

Although the preparation of surgical procedures with the use of 3D printed support tools is still rather expensive, it bears significant potential for the improvement of surgeries. In the past, surgeons had to rely mainly on x-rays, scans and surgical experience for diagnoses and surgical plans (The Verge, 2014). 3D printing offers new possibilities to plan surgical procedures precisely on a case-by-case basis and to validate procedures in advance. This way, surgeries can become more efficient and predictable (interview 8, 2014). Thus, surgical time can be reduced significantly, which both reduces the costs of surgery and directly impacts the quality of patient care (Rockman, 2014; interview 8, 2014).

Development of individualized implants, prosthetics and orthoses

Additive manufacturing in the area of medical manufacturing refers to the printing of non-living materials for medical purposes such as scaffolds, teeth, bones and prosthetics (Barnatt, 2013). To date, health care products are produced as either a mass product or patient-specific. Thereby, the cost-efficiency of mass-produced products usually comes along with losses in individual fit and quality. Patient-specific products are typically hand-crafted and require a long-lasting production process: measurement, order queue, production in workshop, delivery, and possibly modifications for a better fit (EOS, 2013b; Massy-Beresford, 2014).

AM offers the possibility to meet the demand for individualized health care products in a cost-efficient way. At first, the doctor examines the patient and creates a computer scan of the affected body area. After the product has been modeled, which may happen automatically, it is 3D printed, possibly right on site (EOS, 2013b). Hearing aids are exemplary for the advanced adoption of 3D printing technology in production of health care products. Virtually every hearing aid manufactured today comes from a 3D printer (ChicagoBusiness.com, 2014; Sharma, 2013c). Besides hearing aids, there is a wide range of products and tools available through the versatility of 3D printers, as for instance demonstrated by EOS (EOS, 2013b).

For facial and limb prostheses, 3D printing has gained momentum during the past 10 years as well and is gradually being adopted as a common manufacturing method in regenerative medicine (Gibson et al., 2004). Especially the field of patient-specific bone replacement implants experiences increasing popularity as first examples of successful recently performed treatments show. In 2014, for instance, a 71-year old lady received a 3D-printed hip joint which was integrated with her pelvis using stem cells and another woman was transplanted an entire skullcap manufactured in a 3D printer (Eng, 2014; Molitch-Hou, 2014c). Furthermore, the technology of actual bone regeneration is so stable that humans already receive such treatments (interviewee 9).

Next to implants, interviewee 8 also emphasized the potential of AM technologies for the production of orthoses, which are "externally applied devices used to modify the structural and functional characteristics of the neuromuscular and skeletal system" (ISO 8549-1:1989). To date the manufacturing of individualized orthoses is a complicated, multi-step procedure: impression-taking, model-building, model modification and manufacturing of the orthosis. Similar to the other examples in the healthcare sector, an automated and digitalized process using AM technology could simplify this process significantly.

In terms of dental implants, most of them are typically created in a complex hand-crafting process. The dentist takes an imprint of the broken tooth, and then a dental technician models a complete tooth on top of that using wax. This model is then used either to produce a mold or to serve as a stencil for a reductive manufacturing process. The described procedure is predominantly hand-crafting and thus time-intensive and costly (Molitch-Hou, 2014a). Thus, the current adoption of 3D printing in dental medicine is driven by the factors time and cost. State-of-the-art machines demonstrate to have an advantage to prior techniques in both time and cost and they are even capable of printing a range of materials like metals and ceramics (EOS, 2013b).

Since consumers wish for a fast delivery of products (Molitch-Hou, 2014a), a vision is to print these products on demand right where the treatment takes place, for example at the optician or at the hospital itself (Massy-Beresford, 2014). Furthermore, health care products are supposed to integrate with style and fashion. 3D printing is expected to meet the mentioned requirements while at the same time cutting costs by up to 40 percent compared to traditional manufacturing of patient-specific products (Massy-Beresford, 2014). In the end, interviewee 8 assumes that 3D printing will bring about manifold new opportunities in the health care sector. These changes, however, might lead to a transformation of the medical engineering sector, as well as a disruption of traditional manufacturing processes and related professions.

3.2.1.2 3D bioprinting and tissue engineering

According to the Gartner Hype Cycle 2014, 3D bioprinting, i.e. the process of “printing of biocompatible materials, cells and supporting components into 3D functional living tissues” (Murphy & Atala, 2014, p. 773), is at the innovation trigger stage representing an emerging, promising, yet unexplored technology (Gartner, 2014). This statement coincides with current literature and with the perception of interviewee 7, who claims that 3D bioprinting is still at stage of fundamental research. If further advanced, however, 3D bioprinting might bring the science of tissue engineering to the next level and has the potential to disrupt medicine fundamentally (interviewee, 7).

As regards processes of tissue engineering, the striking innovation brought about by AM technology was to add a third dimension (x-, y- & z-axis) to the so far two-dimensional process. Additionally, recent improvements regarding size and resolution have opened up new opportunities for the artificial production of tissue structures and scaffolds (interview 7, 2014). Even though 3D bioprinting is still far from everyday application in clinical processes, first success stories exist. For instance those of a 2-year-old child who received a printed windpipe or a teenager who received an engineered bladder (Atala, 2011; Griggs, 2014). According to academic literature, researchers are already able to print the structural scaffolds required for initial cell seeding (Leukers et al., 2005; Peltola et al., 2008). Furthermore, they are as well able to print two-dimensional and simple three-dimensional tissue structures, like skin, muscle strips and larger blood vessels, which is already revolutionary (Mironov et al., 2003; Moon et al., 2010). According to Mohit Chhaya from IHBI, there were even first trials for 3D-printed breast implants for women who had breast cancer. These are meant to support the shape of the reconstructed breast until the injected fat has been remodeled into a stable form. However, in terms of complex soft organs not a single fully functional one has been printed up to today (Atala, 2014).

3D bioprinting process

Generally, interviewee 7 (2014) describes two approaches for bioprinting:

1. Printing of three-dimensional solid scaffolds, in which respective cells are seeded (e.g. bone graft materials) and then can divide and proliferate according to the scaffold's form.
2. Extraction of specific cell types from tissues (e.g. connective tissue cells, skin cells, bone cells) followed by artificial multiplication; cells are then merged with a concentrated gelatin solution which ensures three-dimensional cohesion during the printing process.

Exhibit 2, adapted from Murphy & Atala (2014), provides a more detailed overview of bioprinting processes and related technology. In becomes evident that 3D bioprinting involves many complexities such as "the choice of materials, cell types, growth and differentiation factors, and technical challenges related to the sensitivities of living cells and the construction of tissues" (Murphy & Atala, 2014, p. 773). Interviewee 7 emphasized that before 3D bioprinting can enter the arena of practical application, for instance in pharmaceutical testing processes, these challenges need to be managed by fundamental research.

3D Printing of organs

Headlines in mass media about 3D bioprinting often raise attention by proclaiming the vision of 3D printed organs as the most radical application of 3D bioprinting. In theory, 3D organ printing is envisioned as follows: A 3D printer prints a scaffold of the organ out of some kind of hydrogel or biodegradable polymer (Gibson et al., 2004). In the same step or in a separate step, cells converted from the patient's stem cells are placed onto the scaffold's surface (Mironov et al., 2003, p. 18). In a chamber, which mimics the environment inside the human body, a controlled cell proliferation is activated (Atala, 2011). There, the organ grows to full size and is then implanted into the patient.

In a Ted Talk in March 2011, Anthony Atala, surgeon and Director of the Wake Forest Institute for Regenerative Medicine in Winston-Salem, NC (US), talks about the importance of regenerative medicine to combat arising health crises as people live longer and organ failure becomes more common (Atala, 2011). In his talk, Atala shows a special 3D printer that builds a prototype human kidney. However, such experimental artificial organs are still far from being ready to implant into human patients (interview 7, 2014).

Step	Explanation	Technological steps / Details
1. Imaging	Gaining a comprehensive understanding of the composition, organization and components of a tissue or organ.	1. Medical imaging technology, such as computed tomography (CT) and magnetic resonance imaging (MRI), in combination with computer-aided design and computer-aided manufacturing (CAD-CAM) is used to collect and digitize architectural information of the respective tissue. 2. The data are processed using tomographic reconstruction to produce 2D cross-sectional images and 3D anatomical representations. Alternatively, also CAD-CAM and mathematical modeling techniques can be used to generate computer-based 3D models. 3. The completed model is interfaced with numerically controlled bioprinting systems (i.e. the 3D-rendered model is divided into thin 3D horizontal slices) to be imported to the bioprinter system.
2. Design approach	After a virtual model has been developed, the design approach for the engineering process has to be chosen. 3D bioprinting is based on three central design approaches:	*Biomimicry*: Biologically inspired engineering that involves the manufacture of identical reproductions of the cellular and extracellular components of a tissue or organ. For this approach to succeed, the replication of bio9logical tissues on the micro scale is necessary. Thus, a profound understanding of the microenvironment (arrangement of cell types, gradients of soluble or insoluble factors) of the extracellular matrix as well as the nature of the biological forces is needed.

	biomimicry, autonomous self-assembly and mini-tissue building blocks.	*Autonomous self-assembly*: Use of embryonic organ development as a guide assuming that the early cellular components of a developing tissue produce their own ECM components and organizes autonomously to form the desired biological micro-architecture and function. *Mini-tissue*: This approach is relevant to both strategies above. Mini-tissues refer to the smallest structural and functional components and building blocks of organs and tissues, such as kidney nephrons. They can be assembled into the larger construct by rational design, self-assembly or a combination of both.
3. Material selection	Choice of printing material that is compatible with biological materials, can be processed via printing machines and provide the desired properties.	Materials currently used in the field of 3D bioprinting are either naturally derived polymers (e.g. alginate, gelatin, collagen, chitosan, fibrin and hyaluronic acid), which are similar to human ECM, or synthetic polymers (polyethylene glycol, PEG). The ideal materials for 3D bioprinting processes have to fulfill several quality criteria and properties: *Printability*: Properties that facilitate handling and deposition by the bioprinter (viscosity, gelation methods and rheological properties). *Biocompatibility*: Materials should not induce undesirable local or systemic responses from the host and should contribute actively and controllably to the biological and functional components of the construct. *Degradation kinetics and byproducts*: Degradation rates should be matched to the ability of the cells to produce their own ECM; degradation byproducts should be nontoxic; materials should demonstrate suitable swelling or contractile characteristics. *Structural and mechanical properties*: Materials should be chosen based on the required mechanical properties of the construct, ranging from rigid thermoplastic polymer fibers for strength to soft hydrogels for cell compatibility. *Material biomimicry*: Engineering of desired structural, functional and dynamic material properties should be based on knowledge of tissue-specific endogenous material compositions.
4. Cell selection	Choice of ells for tissue printing to ensure the correct functioning of the fabricated construct.	Tissues and organs comprise multiple cell types with specific and essential biological functions that must be re-capitulated in the transplanted tissue. This includes both primary functional cell types as well as supportive cell types. Current options for printing cells involve either the deposition of multiple primary cell types into patterns that represent the native tissue or printing stem cells that can proliferate and differentiate into required cell types. The cells used for bioprinting applications must be robust enough to survive the bioprinting process and withstand physiological stresses once transplanted, including physical forces such as shear stress and pressure as well as biological stressors including presence of toxins, enzymes and non-physiological pH.
5. Bioprintin g	The main technologies used for deposition and patterning of biological materials are inkjet, microextrusion, and laser-assisted printing. Different features of these technologies should be considered in light of the most important factors in 3D bioprinting, which are surface resolution, cell viability and the biological materials used for printing.	*Inkjet bioprinting (drop-on-demand printers)*: Most commonly used printer type for biological applications. The advantages include high print speed, low cost and wide availability. Studies have demonstrated that the localized heating does not have a substantial impact on the stability of biological molecules or the viability or post-printing function of mammalian cells. However, the risk of exposing cells and materials to thermal and mechanical stress, low droplet directionality, non-uniform droplet size, frequent clogging of the nozzle and unreliable cell encapsulation pose considerable disadvantages for the use of these printers for 3D bioprinting. Examples of the inkjet bioprinting approach include the regeneration of functional skin and cartilage. *Microextrusion bioprinting*: Microextrusion bioprinters function by robotically controlled extrusion of a material, which is deposited onto a substrate by a microextrusion head. Microextrusion yields continuous beads of material rather than droplets. Microextrusion bioprinters can handle a myriad of materials, such as hydrogels, biocompatible copolymers and cell spheroids. For microextrusion bioprinting, researchers often exploit materials than can be thermally cross-linked and/or possess sheer thinning properties. The main advantage of microextrusion bioprinting technology is the ability to deposit very high cell densities. Microextrusion bioprinters have been used to fabricate multiple tissue types, including aortic valves, branched vascular trees and in vitro pharmokinetic as well as tumor models. *Laser-assisted bioprinting*: Laser-assisted bioprinting (LAB) is based on the principles of laser-induced forward transfer. The technology has been successfully applied to biological material, such as peptides, DNA and cells and is increasingly being used for tissue- and organ-engineering applications. Because LAB is nozzle-free, the problem of clogging with cells or materials that plague other bioprinting technologies is avoided. Furthermore, LAB is compatible with a range of viscosities and can print mammalian cells with neglible effect on cell viability and function. However, the high resolution of LAB requires rapid gelation kinetics to achieve high shape fidelity. The high costs of these systems is also a concern for basic tissue-engineering research. Laser 3D printing has been used to fabricate medical devices.
6. Applicatio n	Application of the 3D printed tissue.	Application can either happen via (1) maturation, (2) implantation of the 3D printed structure or (3) *In vitro* testing.

Exhibit 2: Overview of the 3D bioprinting process. Taken and adapted from Murphy & Atala, 2014, p. 773-f

Alongside Atala, another significant bioprinting pioneer is Gabor Forgacs from the University of Missouri and founder of Organovo, a company dedicated to the creation of tissues on demand for research and surgical applications. In 2009, Organovo collaborated with medical equipment manufacturer Invetech and created the NovoGen MMX, the world's first commercial bioprinter. In December 2010, Organovo used a NovoGen MMX to create the first bioprinted human blood vessels. In 2013, it reported the successful bioprinting of human liver tissue and that they have implanted nerve grafts into rats. Researchers at Huazhong University of Science and Technology in China, on the other hand, claim to have successfully created living human kidneys by using 3D printing technology. However, the application with regard to real human bodies remains far from reality today. Barnatt (2013) estimates that a first implant of even a simple bioprinted organ like a kidney is unlikely to occur until the late 2020s. The experts interviewed for this study go even further and state that we are still about 40 to 50 years from the first printed organ (interview 7, 2014; interview 9, 2014).

3.2.1.3 Outlook: 3D printing has significant market potential in healthcare

An analysis by the market research organization Transparency Market Research (TMR, 2013) estimates the global 3D printing in medical application market to reach US-$ 965.5 million by 2019 compared to a market size of US-$ 354.5 million in 2012. This represents a compound annual growth rate (CARG) of 15.4%. In 2012, medical implants accounted for the largest share of this market, followed by surgical guides and surgical instruments. It is also the medical implant market (including dental, orthopedic and cranio-maxillofacial implants) that is expected to grow at the highest CARG of >15% from 2013 to 2019 (TMR, 2013). As aforementioned, the field of bioengineering is still at a stage of basic research and thus accounts for the smallest market share. From a nation-specific perspective, TMR (2013) expects Europe to experience the highest growth rate in the upcoming years.

The healthcare sector is therefore probably one of the most promising applications fields for 3D printing technology. Interviewee 8 (2014) describes the possible benefits in the area of medical manufacturing as a win-win situation: On the one hand, 3D printing provides doctors and medical institutions with new solutions to plan treatments and to develop surgical guides, as well as implants and prosthetics. Furthermore, these new solutions increase treatment efficiency, which directly translates into significant economic cost savings. On the other hand, 3D printed implants and surgical guides are highly adaptable to individual requirements and thus increase patient-fit.

In the area of 3D bioprinting, interviewee 7 sees great potential for the pharma industry in the near future. Further advancements in 3D bioprinting technology will allow the improvement of artificial tissue models that can be used for medical testing and simulations. This might translate in a decrease of animal testings and cost savings. However, as stated, 3D bioprinting is still at an early stage and requires a lot of fundamental research. Research is needed on all fronts, starting with the bioprinting technology as such. For instance, printing methods have to be developed that keep cells alive during the printing process since most technologies use heated print heads (Murphy & Atala, 2014; interview 7, 2014). Second, biomaterials, cell sources and methods of vascularization have to be improved. For instance, one of the greatest concerns is the construction of a vascular system to keep the cells alive (Maher, 2013). Also, structures printed up to now cannot take sufficient physical load and the question of the right base material to use still persists (Finnegan, 2014; Peltola et al., 2008). Lastly, innervation and maturation are additional research areas.

In sum, research is required in all fields of medical 3D printing including technical, material and cellular aspects (interview 7, 2014; interview 8, 2014; Murphy & Atala, 2014). Addressing these challenges will require an interdisciplinary approach, combining knowledge from engineering, biomaterials science, cell biology, physics and medicine (Murphy & Atala, 2014). Thus, both interviewee 7 (2014) and interviewee 8 (2014) favor the idea of interdisciplinary clusters for AM in medicine that foster knowledge exchange and trigger joint research projects. Germany as a world leader in medical equipment and machinery as well as in 3D printing technology (Lohmüller, 2011; Mourdoukoutas, 2013), is in a favorable position to foster research in that area while benefitting from the large market potential in that area.

3.2.2 3D food printing and nutrition

There is a discussion whether and to which extent 3D printing can be used for artificial food production based on carbohydrates, proteins and other nutrients (Mims, 2013). One of the pioneers in that area is Anjan Contractor, a mechanical engineer by training, whose company Systems & Materials Research Corporation got a 125,000$ grant from NASA to create a first prototype of a universal food synthesizer[1]. The motivation of NASA was to come up with a new way to ensure food supply in space. Contractor, however, has a much bigger idea for his invention. In May 2013, he told the online business news blog Quartz that he "sees a day when every kitchen has a 3D printer, and the earth's 12 billion people feed themselves customized, nutritionally-appropriate meals synthesized one layer at a time, from cartridges of powder and oils they buy at the corner grocery store" (Mims, 2013).

While Contractor's vision is still far from reality, 3D printed food offers some notable opportunities to solve emerging societal challenges. For instance, elderly people with swallowing problems or different dietary needs could profit from the technology. However, there are some major challenges to be overcome in order to make printed food a decent alternative to conventionally made food.

3.2.2.1 Functionality

One of the first prototype 3D food printers, which is currently under development, is based on a piece of open-source hardware, namely the second-generation RepRap 3D printer (Mims, 2013). 3D food printers are envisioned to work similar to typical inkjet printers. However, instead of different colors of ink, there are various cartridges filled with liquefied or powdered food (Pearse, 2014). The cartridges contain nutrients like protein, complex carbohydrates, sugars or other basic building blocks. In order to make the food stick together, a gelation agent is added to the liquid in the cartridges (Pearse, 2014).

3.2.2.2 Food supply for people with special needs

By 2025, more than 20% of all Europeans will be aged 65 and above. 3D printed food could be a solution for the one in five people over the age of 50 who suffer from dysphagia (i.e. swallowing problems) (Ekberg et al., 2002). Those people's larynx, which is responsible to guide food to the stomach instead of the lungs, does not function properly, and thus food can get into the respiratory tract without being noticed. This can lead to serious health issues like pneumonia and renal failure, which might even result in death (Pearse, 2014).

It is estimated that up to 60 percent of people in nursing homes suffer from that condition and thus can "eat" liquefied meals only. This can also cause psychological effects such as frustration and depressions. Therefore, scientists are working on reconstructing food items into a more appetizing and still digestible form. Chicken fillets, for example, are cooked, pureed and

[1] For a short video on the printer, see: http://www.youtube.com/watch?v=55NvbBJzDpU

strained so that the jellified version can be safely eaten as it is supposed to melt in the mouth. At the moment, such processed food is very time-consuming and available to a restricted number of people only. However, the European Union invested heavily into a three-year 3D food printer technology. It is estimated that by 2015, such safe meals will be available to a lot more people.

Scientists also think that printed food can be personalized by adding specific nutrients, like folic acid, or vitamins to it. As a result, people could get meals which are tailored to their individual demands (Pearse, 2014). Moreover, the powdered nutrients are shelf-stable for up to 30 years, meaning that each cartridge can be fully exhausted before it is returned to the store. As a result, food would no longer have to be wasted due to spoilage (Kline, 2013).

3.2.2.3 Outlook: Food printing might increase quality of life

3D food printing technology is currently at an early prototype stage, thus it will still take some years to develop and enhance the functionalities until food printing is actually possible at a larger scale. Furthermore, important food-types such as vegetables, fruits or meat are not natively printable. In order to be able to print these items, significant reformulation efforts would have to be undertaken. In contrast, there are many nourishments which are easier to print but less healthy such as cake frosting, processed cheese or chocolate. Therefore, one big challenge will be to find ways of printing a wide variety of healthy and sustainable food with only a limited set of materials (Cohen, 2013).

3.3 3D Printing in the consumer market

This section explains how 3D printing is received by consumers and how it is already or may change the world of consumers. The chapter is structured into three parts. First, the status quo and current trends of 3D printing in the consumer and end-user market are described. Second, four different case studies describe important actors in the close-to-consumer market of 3D printing. The third part provides an outlook of how the world of 3D printing may look like for the consumer in 10-15 years from now by describing four scenarios.

3.3.1 Status quo and trends

While additive manufacture ng technologies have already gained a strong position in the industrial sector, the development in the consumer market is still at an early stage. 3D printing is not yet a household technology, but it is taking its first steps into the mainstream as a growing number of early adopters familiarizes with the technology and owns a 3D printer in their homes. Most of these early adopters are so-called *Makers*. Makers can be compared to power users for software companies. Similar to hackers who like to alter software to their will, Makers bend technology to their will and have coined a whole movement – the Maker Movement (Lipson & Kurman, 2013).

According to interviewee 13, developments in three key areas have paved the way for the adoption of 3D printing in the end user market and have led to the status quo. These include the access to digital production capacities, the availability of affordable, easy to use 3D design software, and the broad establishment of maker-to-consumer platforms.

Originating from industrial 3D printers, which have been used since 1982, so-called desktop printers are an emergent and affordable smaller version for end users. The industry for desktop 3D printers started 30 years ago, when a number of startups filed patents for small consumer printers, serving a niche market of the 3D printing industry (West & Kuk, 2014). However, due to rather high prices of printers, the industry has not grown during the first two decades. Only with the expiration of the first patents and the formation of the open-source community RepRap, which freely disseminated 3D printer technology, small startups were able to enter the market. With their entry, both price and the size of printers began to decrease while quality improved (West & Kuk, 2014). Both, falling prices and the enormous reduction of personal 3D printers in size (Cole, 2014; Huffington, 2014) reveal an ongoing trend in the AM industry and may ultimately lead to the democratization of manufacturing (Regalado, 2013).

Additionally, an increasing number of businesses offering 3D printing services has evolved. These businesses subsumed under the term “3D Printing as a Service”, offer Makers capacity to realize their design ideas without owning an additive manufacturing machine themselves (interview 13, 2014).

At the same time, the broad availability of easy to operate 3D design software (interview 13, 2014) has fuelled the adoption of 3D printing. Used for creating design files through the mathematical representation of three-dimensional surfaces of objects, 3D modeling software is a prerequisite for printing three-dimensional objects (Lipson & Kurman, 2013).

The first rather primitive computer-based design tools appeared in the 1950s and were exclusively used by scientists for crude computer-based simulations (Lipson & Kurman, 2013). Early commercial design software came onto the market only decades later and was prohibitively expensive – US-$ 50.000 to US-$ 100.000 per license (Grandinetti, 2014). But just as 3D printers have significantly dropped in price, so has CAD design software. Today, a range of open source 3D software is freely available online, opening up the design space for a much wider, non-professional audience (Grandinetti, 2014).

Besides the high price, technical complexity and weak usability of early design software have been large barriers for the main public to engage in 3D modeling. Due to its origin in the manufacturing and computer animation fields, design software was initially developed to meet the requirements of engineers and hence included highly technical features. However, in the past years, the market has undergone a rapid evolution. The audiences for design software have changed from broadly technical to hobbyists and design enthusiasts (Sharma, 2013b). Consequently, many incumbent software providers have converted their industrial grade design technology into very simple, intuitive tools (Sharma, 2013b).

Finally, the establishment of maker-to-consumer platforms has triggered the widespread use of 3D printing technologies by private persons (interview 13, 2014). Maker-to-consumer platforms and websites allow designers or other individuals to share their 3D models with other users. Thereby, these platforms grant non-designers access to design files, enabling a much wider audience to engage in 3D printing technologies.

3.3.1.1 Speed, price and material

The market of desktop 3D printers is rapidly expanding as new companies and printer models are emerging in ever shorter time sequences (Make, 2014). While still a nascent market, the speed of development and rise in buyer interest are pressing hardware manufacturers to offer easier-to-use tools that produce consistently high-quality results (Gartner, 2013a). Today, Makerbot Industries with its Replicator 2 and Replicator 2X models has established as the dominant player accounting for more than 60% of total consumer 3D printer sales (Sharma, 2014). The various versions of the open source RepRap 3D printer make up the second largest category followed by the Ultimaker models (3DHubs, 2014).

The print speed of personal printers tends to increase with each new generation of products. Makerbot's Replicator 2X prints objects twice as fast as its predecessor, the Replicator 2, reaching a speed of 200 mm/second (see table 7). The Ultimaker models with printing speeds of up to 400 mm/second are even faster and take the leading position. Yet, even with speeds in this magnitude the printing of a rather small object such as a smartphone case takes around 30 minutes. For objects with dimensions in the area of 15cm x 15 cm x 15 cm, the printing process even lasts several hours. Hence, compared to traditional means of manufacturing that produce products by the minute, 3D printing is still not yet fast enough for our "mobile, want-it-now world" (McCue, 2014).

Another ongoing trend within the personal 3D printer market reveals the falling prices of hardware. The cheapest 3D printers already reached prices of only several hundred Euros. In general, 3D printer prices are expected to further decrease during the next years due to competitive pressures and higher shipment volumes (Gartner, 2013a). Today, personal 3D printer prices range from € 1.000 to € 2.000€, with the exception of the low-cost open source self-assemble kits by RepRap that start at € 300. To become a mainstream technology, desktop 3D printers are still too costly. Thus, their adoption in private households will highly depend on whether prices will fall to a level that will allow average consumers to buy a desktop 3D printer.

Today's personal 3D printers work predominantly with plastic. Although the word "plastic" is often connoted with low-cost materials, 3D printing plastic is not necessarily cheap. In fact, the costs of filament plastic amount to a significant part of the costs of running a 3D printer with about € 30 per cartridge (Lipson & Kurman, 2013). Most 3D printer manufacturers offer their own proprietary material and lock in their customers via a "razor and blades-business model". That is, producers give away the 3D printers at low prices but require customers to buy proprietary, vendor-specific filament – the only ones that fits in the printer – at rather high prices (Lipson & Kurman, 2013).

Table 7: Overview over most popular desktop 3D printers[2]. Source: Own research.

Model	**Makerbot Replicator 2**	**Ultimaker 1**	**Makerbot Replicator 2X**	**Prusai3 Single Sheet Frame/Box Frame**	**Ultimaker 2**
Producer	Makerbot Industries	Ultimaking Ltd.	Makerbot Industries	RepRap	Ultimaking Ltd.
Maximal object size	28,5 x 15,3 x 15,5 cm	21,0 x 21,0 x 22,0 cm	25 x 16 x 15 cm	20 x 20 x20 cm/ 20 x 20 x 27 cm	23 x 22,5 x 20,5 cm
Print speed (mm/sec)	90	~ 400	200	80-200	30-300
Print time (min)	18 min for an average smartphone case	30 min for an average smartphone case	10 min for an average smartphone case	>40 min for an average smartphone case	30 min for an average smartphone case
Materials	PLA & Flexible	PLA & ABS (supported), PCL, HDPE, PP, PMMA (known to work)	ABS, PLA, & Flexible	PLA & ABS	PLA & ABS
Price per Printer	~1.604,00 € (	1.194,00 €	2.790,00 €	300-1000 €/ 300-800$	1.895,00 €
Price of Filament	~35,00 €, 98 € / Cartridge (1kg)	32,00 € / Cartridge (0,75kg)	~15,32 €, ~98 € / Cartridge (1kg)	n.a.	32,00 € / Cartridge (0,75kg)

3.3.1.2 Trends

Today's desktop 3D printers use fused deposition molding (FDM) as a manufacturing process. Yet, with the expiration of patents for 3D printing technologies, machines based on alternative additive manufacturing processes, such as stereolithography have recently entered the market for personal 3D printers. The recent release of the first desktop 3D printers based on selective laser sintering is only the logical advancement in a rapidly evolving industry (Molitch-Hou, 2014f). The Ice9 and the Ice1 are laser sintering printers for home use priced at around 25.700€ and 9.800€ and are rather expensive. Both printers have substantial printing sizes, with the Ice1

[2] Selection of printers based on 3D Hubs' most recent Trend Report of June 2014 encompassing an international community of 6.887 registered local 3D printers (3DHubs, 2014). It has to be considered that the numbers are slanted somewhat by the fact that 3D Hubs is particularly popular in Europe, where it launched first. This accounts for Ultimaker's huge documented popularity. The printer sold in greater numbers in Europe, as compared to other continents.

comparing to most desktop FDM machines and the Ice9 larger than most. At the same time, both printers produce much finer surface finishes and definition than FDM-based machines and will not need added support structures, since the powder bed acts as the support (Molitch-Hou, 2014f).

Alongside innovations in the manufacturing processes, improvements in the materials printable have been made for household 3D printers. MatterFab has only recently launched an affordable 3D metal printer for end users paving the way for broader application areas of personal printers. Because, over the past twenty years, sensors, computers, and other components necessary for 3D metal printing have reduced in price, Burris and his partner, Dave Warren, were able to develop the prototype for a low-cost 3D metal printer, which is now hitting the market (Molitch-Hou, 2014d).

Apart from constant innovations in the 3D printing hardware market, the advancement in 3D software is just as groundbreaking. Software providers have realized that the "future of design software is to make it easier to move back and forth between software and reality" (Lipson & Kurman, 2013) meaning that their goal is to make it easier for users to manipulate digital data. Teams at Carnegie Mellon University and Berkeley University of California have recently launched their Object Manipulation 3D (OM3D) software, which makes it possible to fully manipulate a 3D object within a regular 2D photograph (Sher, 2014a). OM3D uses the publicly available 3D models that correspond to the object needed to be modified and seamlessly works it into the photo. As a result, any hidden area of the 2D object's geometry becomes visible in the 3D representation. In this way, object manipulations that would be impossible in traditional 2D photo-editing programs are enabled, such as turning a car over, making a paper-crane flap its wings, or manipulating airplanes in a historical photograph to change its story (Kholgade, Simon, Efros, & Sheikh, 2014). In another context, this revolutionary software could be applied to make pictures come alive by enabling users to print a single object of an image in 3D, thereby rendering the lines between 2D and 3D even more blurry.

The effects of personal AM machines on the work environment are manifold. Desktop 3D printers open up new opportunities for consumer empowerment and ultimately lead to new forms of production and collaboration. Individuals are provided the tools, either through affordable 3D printing hardware or streamlined outsourcing to engage in the act of making directly (Ratto & Lee, 2012).

Alongside this empowerment, considerable shifts in consumer behavior can be noted. In the contemporary world, consumers increasingly wish for individualized experiences and expect that products are tailored to their specific needs. The newly emerging modes of customization are decidedly consumer-driven. The "prosumer" (Ritzer & Jurgenson, 2010) is a model that puts the consumer at the centre of product innovation and has been exerted most notably on digital products including software. Now, facilitated by digital desktop fabrication, prosumer modes of production are traversing from the digital to the material (Ratto & Lee, 2012). With desktop 3D printers, consumers can design and produce new products easily themselves – tailored exactly to meet their particular needs.

Also, so-called co-creation platforms are distinct types of mass customization that provide prosumers with the opportunity to interactively personalize products in a way that encourages them to feel more like 'designers' of objects rather than passive recipients. For example, end users can download a certain basic design file from an online database, the specifications of which they then alter to their distinct wills.

As the boundaries between digital and physical production become increasingly blurry, so too do conceptions of labor (Ratto & Lee, 2012). “Commons-based peer production” (Benkler, 2006), p.62), which is enabled by digital networks, has proven transformative in the digital world by introducing modes of production of large projects (Linux, Wikipedia, etc.) based on collaboration and the widely distributed contributions by many, as opposed to mass production from a centralized source. Hence, 3D printing may act as a catalyst for cloud manufacturing a network of decentralized manufacturing firms (Lipson & Kurman, 2013).

Not only does 3D printing allow for decentralized production, also it promotes the division and distribution of labor. While traditionally the processes of product idea, design and manufacturing were done by the same entity, 3D printing allows and even encourages splitting the work. Designers and manufacturers do not necessarily have to be the same person anymore, neither do they have to know each other personally. This way of working opens up whole new opportunities spurring product innovation.

3.3.1.3 User needs and motivation of end-users

The diverse business models emerging in the consumer 3D printing market offer consumers the possibility to fulfill their needs using 3D printing technology. Depending on different needs and situational requirements, four categories of items, as depicted in table 8, can be identified. These categories build on the theory of Maslow’s pyramid of needs (Maslow, 1943) and a model by Marshall Rosenberg (Rosenberg, 2003).

Table 8: Consumer needs fulfilled by 3D Printing. Source: Own research.

Type of Item	Need Fulfilled	Examples
Functional Items	Necessities	Spare Parts, Tools
Entertainment Items	Leisure Needs/ Belonging and/or Self Esteem	Dice, Board Games, Miniatures
Customized Items	Self-Actualization Needs - Creativity	Jewelry, Phone Cases, Lamps
Specialized Items	Self-Actualization Needs - Problem Solving	Prototypes, Prosthetic Hands

Maslow’s pyramid including physiological needs as the basic stage, safety needs, love or belonging, esteem and self-actualization as the highest stage of needs, claims that humans enter a new stage of needs only if they could fulfill the needs of the stage below (Maslow, 1943). Marshall Rosenberg developed another model that extends Maslow’s basic categories. He also includes the categories of physical nurturance, autonomy, independence and spiritual communion, which can also be found in Maslow’s pyramid. In addition, he extends the model with more concrete needs for entertainment, celebration and play (Rosenberg, 2003).

The following section applies these theoretical models of human needs to desktop 3D printing to identify the needs consumers aim to fulfill by printing specific items.

Functional items are printed by consumers with the purpose to recreate or improve conditions and tasks in their daily routines. By that, functional items help users fulfill the needs of basic necessities such as replacing a broken part or printing a part that doesn’t exist or isn’t accessible on the market. Spare parts and tools as well as mechanical parts are examples for functional items with which the consumers can fulfill basic needs.

Based on Maslow's theory, humans need self-esteem and a feeling of belonging once basic functional and physiological needs are fulfilled. 3D prints of *entertainment items* fulfill this need and also the need for recreation, play and spiritual needs (Rosenberg, 2003).

3D printing creates an opportunity for customization. By producing one item at a time, the buyer can be engaged when creating the product and his input shapes the final object (Gannes, 2014). However, *customized items* not only fulfill the need for an individualized item, rather target consumers' need for self-actualization through the process of creative development 3D printing offers. Statistics show that on Shapeways for example, more than 50% of the objects existing in 2013 can be classified as "entertainment" items: 23% from the models are miniatures, 17% art objects and 11% games and toys (Shapeways, 2014b).

Specialized items are items that the average user does not need, but they add great value for a specific group of users with particular needs. Consumers have the possibility to serve their special needs like rare illnesses by developing and printing their personalized solution. One example is a father who designed and printed a prosthetic hand for his son due to the lack of financial resources for buying one (Huffington, 2013). Consumer 3D printing fulfills consumers' needs by providing a tool to realize their own solutions to their personal problems.

3.3.2 Case studies

3.3.2.1 3D printer manufacturers

General Description: Desktop 3D printers make additive manufacturing available for consumers (PCmag, 2014). Originating from AM machines, which have been used since 1982 (redOrbit, 2014), so-called desktop 3D printers are an emergent and affordable smaller version for end consumers. With the expiration of the first patents for FDM machines and the formation of the open source community RepRap, which freely disseminated 3D printer technology, small startups were able to enter the market. With their entry, prices and also the size of the printers started to decrease while quality improved (West & Kuk, 2014). Since the patent for SLS printing technology expired in January 2014, companies started to offer printers based on SLS in addition to the prevailing FDM technology (Templeton, 2014).

Case Description: MakerBot, the most noted manufacturer for consumer 3D printers (Sharma, 2013a), was founded by Bre Petis in 2009 and is located in Brooklyn, New York (Huffington, 2014). The firm is one of the most successful startups emerging out of the open-source community environment and developed from a startup with deep Do-it-yourself (DIY) roots to one of the most important player in the market (Lipson & Kurmann, 2013; Sharma, 2013a).

Building on the open hardware technology of RepRap (RepRap.org, 2013), MakerBot was the first to launch a line of commercial and affordable 3D printers (interview 14, 2014; Huffington Post, 2014).

MakerBot offers 3D printer kits and ready-assembled printers for consumer and small businesses (Sharma, 2013a). The simple and easy-to-use printers are offered in different variations which are segmented in three categories. Table 9 provides an overview of MakerBot's product portfolio. The Mini is the smallest and lightest printer suitable for amateurs without deep technical knowledge. The Replicator is bigger and heavier and tailored to a more experienced and skilled user base. It is equipped with an improved layer dissolution of the prints and hence, fulfills higher requirements (MakerBot, 2014). The tallest and most expensive printer is the ultra-large Z18, which is targeted at small manufacturing shops (Biggs, 2014). All printers are based on the FDM technology and possess Wifi and USB ports (MakerBot, 2014).

Table 9: Overview of MakerBot's product portfolio. Source: Makerbot, 2014

Product Name	Price	Measures	Weight	Layer Dissolution
MakerBot Replicator Mini	1.599 €	31,0L X 29,5B X 38,1H cm	8 Kg	0,2 mm
MakerBot Replicator	3.190 €	52,8L X 44,1B X 41,0H cm	16 Kg	0,1 mm
MakerBot Replicator Z18	6.990 €	49,3L X 56,5B X 85,4H cm	41Kg	0,1 mm

Up to now, the company has sold over 22.000 desktop 3D printers (Lobosco, 2013). MakerBot aims at high consumer-friendliness through affordable prices and simple printer design (Lipson & Kurmann, 2013). In 2013, MakerBot has been acquired by Stratasys, an established manufacturer which offers mainly industrial rapid prototyping based on FDM technology, at an amount of $400 million (Huffington Post, 2014; Sharma, 2013a).

Competitors: Besides MakerBot many startups have entered the consumer 3D printing market, offering mainly FDM technology based printers (Templeton, 2014). Examples are Ultimaker, based in the Netherlands, and AIORobotics, based in the US (Ultimaker, 2014; AIORobotics, 2014). Sharebot, an Italy based producer of desktop 3D printers is extending its FDM printers with the SLS technology and is one of the first to offer this technology affordable for the consumer market (Sher, 2014b).

3.3.2.2 3D model marketplaces and search engines

General Description: 3D model marketplaces are virtual maker-to-consumer platforms that allow designers or other individuals to share their 3D models with other users. The foundation for the sharing community or peer-to-peer movement was laid by services like Napster, which allowed users to directly connect to each other and transfer files from one computer to the other. Through these services, people realized for the first time that they could have a social impact using the Internet (Oram, 2001, p. viii). In the following years, pioneers like Wikipedia's Jimmy Wales and YouTube's Chad Hurley pushed the idea further, resulting in what we now call the Maker Movement. Today, these kinds of platforms are ubiquitous and have influenced behaviors of online social networks (Botsman & Rogers, 2010). Maker-to-consumer platforms are an offspring of this development and allow people without any design aspirations to print 3D objects, thereby pushing the application of 3D printing technologies further.

The scope of these 3D printing platforms ranges from the sole provision of a platform for the exchange of 3D files to an end-to-end service including printing and shipping of the desired object. The latter form will be covered separately in section 3.2.2.3.

Case Description: Thingiverse is a design community for discovering, making and sharing 3D-printable models that was founded in November 2009 by Zach Smith. The platform is hosted by MakerBot Industries, a New York City based hardware manufacturing company specialized in 3D printers (see section 3.2.2.1). With over 100.000 3D models and 130.000 members, Thingiverse is the world's largest 3D printing community. Thingiverse encourages users to publish their files under a creative commons license. This allows users with little previous experience or technical expertise to build on existing 3D models and to create their own customized versions, which therefore maximizes the number of available files. Opposed to 3D printing marketplaces, files offered on Thingiverse.com can be downloaded free of charge. Thingiverse solely acts as a platform for the exchange of files and does not provide any printing services (Thingiverse.com, 2014). The goal of Thingiverse is not to make money in the first place. The platform is intended to create content and awareness for its parent company MakerBot. Content creation is important, as MakerBot was one of the first companies to produce 3D printers and they were facing a common problem for companies relying on network effects: Their 3D printers, which mainly target private persons, were not attractive as there were no files that could be printed. Simultaneously, the low diffusion of consumer 3D printers caused a lack of available 3D models. Thus, MakerBot decided to overcome the problem by founding a platform to generate content for their 3D printers. According to interviewee 13 and 14, Thingiverse's content still lacks a clear structure and is to some extent of medium quality. This stands out against their first mover advantage, allowing more and more competitors to enter the market.

Competitors: Another provider of free 3D printing models is Wamungo. The Munich based company offers models of 21 different categories ranging from toys to car utensils. Identifying themselves as the platform of the maker-movement, Wamungo organizes a 3D print award seeking broader attention and additional members (Wamungo.de, 2014).

Yeggi, another German based company, offers their customers to search among thousands of 3D model files from different websites. After inserting a particular search term, the platform provides the user with various possibilities where he can download the model for free.

3.3.2.3 E-commerce: 3D printed object marketplaces

General Description: The business of 3D printed object marketplaces consists of two parts: a virtual and a physical one. The virtual part is a two-sided online platform that connects designers and end-users similar to the 3D model marketplaces. However, in comparison to these, 3D printed object marketplaces integrate production and shipping of the 3D objects as the physical part in their business model. Thus, users receive the printed objects instead of the 3D model files and designers can decide to keep the models themselves confidential.

Case Description: Shapeways was originally founded by Peter Weijmarshausen, Marleen Vogelaar, and Robert Schouwenburg in the Royal Philipps Electronics incubator in the Netherlands in 2007 and is today based in New York City. It is a 3D printed object marketplace that provides value to designers and end-users. It provides designers with the infrastructure to open their own online shops for offering their designed objects to the world. Designers can upload their model files, which they created before using any 3D design software or use a simple online design software. End-users can browse the huge range of designer stores and offered products, sometimes slightly customize the products by choosing from various material or colors, and order the objects. Individuals and companies can also send their own 3D model files in order to receive printed objects without selling it to third parties. Shapeways categorizes all offered objects and arranges them in an online catalogue using seven categories, which also reveal the current focus. Table 10 provides an overview thereof (Shapeways, 2014a).

Table 10: Overview of Shapeways' product catalogue. Source: Shapeways, 2014a

Category	Description	Number of Products*
Gadgets	Mainly functional items of small robotics, drones, etc. aiming at tinkerers/makers	> 17.000
Accessories	Belts, cases for smartphones and other devices, keychains, etc.	> 19.000
Jewellery	Bracelets, cufflinks, earrings, necklaces, rings, etc. available also in gold and silver	> 28.000
Art	Artistic objects like sculputures, and 3D expressions of mathematical art and memes	> 28.000
Home	Household objects like vases, cups, egg cups, clocks, lamp shades	> 8.000
Games	Dice, puzzles, complements for board games, spinning tops, etc.	> 67.000
Miniatures	Figurines and miniatures of vehicles, model trains or the like	> 62.000
		* Objects can appear in more than one category

Besides their online platform, Shapeways' key resources are their production sites consisting of more than fifty 3D printers (Lipson&Kurman, 2013). These applied machines are not desktop 3D printers as described in section 3.2.2.1, but rather professional high quality, highly priced industrial additive manufacturing machines from the company EOS GmbH (Halperin, 2014). Shapeways aggregates thousands of orders to ensure a high degree of machine utilization. Thus, economies of scale do not only lead to profitability of the machines – even though used for producing everyday objects for end-users – but also allow Shapeways to offer its customers a large variety of different materials. In total, more than 120.000 products per month are printed and shipped (Shapeways, 2014b).

The revenue model works similar to Apple's AppStore: for objects sold through the Shapeways platform, designers receive 10% of the price while 90% remain with Shapeways.

In addition to that core of the business, Shapeways also helps designers with tutorials, tools, forums and thus, manages an active online community around the topic of 3D design and puts designers in contact with companies and brands looking to get into the upcoming topic of 3D printing (Kurutz, 2014; Shapeways, 2014a). The on-demand production model of Shapeways lowers risks and entry barriers for designers to start their own businesses. Even though most designers with products on Shapeways create objects as a hobby or as a side job, first companies were founded basing their business on the Shapeways infrastructure to produce and offer their products (Kurutz, 2014).

Competitors: Other players using similar business models for entering the 3D printing market are the France-based Sculpteo, the Belgium-based i.Materialize, the Texas-based Kraftwurx and since July 2014, also US-based Amazon.com. The newly started Amazon 3D printing store sees a special value in offering further customization options to customers (Krassenstein, 2014a; Amazon, 2014; i.Materialize, 2014; Kraftwurx, 2014; Sculpteo, 2014).

3.3.2.4 In-store 3D printing services

General Description: In-store 3D printing services offer customers to use and experience 3D printing so that also non-tech-savvy end-users can try out the new possibilities of 3D printing technologies without having to invest a lot of their money and time. Besides printing available 3D models (e.g., smart phone cases) from the store or from model marketplaces (see 3.2.2.2), in-store 3D printing services also offer 3D scanning and support for using 3D modeling software to customize models. Usually the service is combined with sales of 3D printing hardware and, thus, offered by retail companies.

Case Description: Staples was one of the first large retailers to sell 3D printers and materials to consumers (Karlin, 2014). They also already started in 2013 to experiment with a 3D printing service in Europe (Brustein, 2014; Karlin, 2014). For this service, which they called "Staples Easy 3D", the company cooperated with Mcor Technologies – a company that sells 3D printers, which use paper as material and are able to print multi-colored objects. However, it was not yet a full-in-store service, but rather a service similar to the above described 3D object marketplaces (Senese, 2012; Sharma, 2013c). Since April 2014, Staples cooperates with the 3D printing company 3DSystems to test "3D printing as a service with immersive 3D printing experience centers" (3DSystems, 2014) in New York City and Los Angeles as the first two locations in the United States (Brustein, 2014). In these experience centers, customers can use 3D printers to create personalized 3D objects. The purpose today is not mainly to sell the printing service, but rather to let consumers and small business owners learn about the possibilities of 3D printing, and vice versa: Staples and 3DSystems aim to learn more about possible use-cases and about the development of the desktop 3D printing market by interacting with their customers. Thus, both companies have experts and graphic design consultants in both experience centers for helping customers, which are new to the area of 3D printing, to use 3D equipment. Besides the 3D printing, customers can also use 3D scanning photo booths for example to capture their own faces as 3D images for customizing figurines. 3D objects can be printed instantly in-store or in case of a longer printing time they can also be printed through 3DSystems and shipped to the customers (3DSystems, 2014; Brustein, 2014; Marks, 2014).

Competitors: The San-Diego based UPS Store collaborated with the Israeli-American 3D printer company Stratasys and together, they launched a test program of retail 3D printing services in six of their shops in the US (3Ders, 2013c; Stratasys, 2013). UPS was the first US-wide retailer testing in-store 3D printing services (UPS, 2013). Florida-based OfficeDepot also cooperates with 3DSystems to offer first in-store test centers (Sharma, 2013c). iGo3D is Germany's first in-store 3D printing service shop. The so-called iGo3D concept store is located in Oldenburg and opened in September 2013. Besides in-store services, it also acts as a 3D printing hardware retailer without focusing on only one main 3D printing manufacturer as partner, but rather offers a range of 3D printers (3Ders, 2013b; iGo3D, 2014).

3.3.3 Outlook: The world of 3D printing from the consumer perspective

As described above, 3D printing is today nearly only used by tech-savvy early adopters, the so-called 'makers'. This section provides a glimpse into the future of 3D printing from the eyes of a usual consumer. But as predictions are very difficult, especially if they are about the future as it was allegedly formulated by Mark Twain, this is not a forecast, but rather a description of four different possible scenarios that might evolve in the upcoming years. These scenarios were partly developed in the CDTM course '3D printing' and are based on an extensive literature review, conducted expert interviews and fruitful discussions of researchers and students. Possible signposts pointing into the direction of the presented scenarios are given with each scenario descriptions and an evaluation of all four scenarios analyzing expert opinions on future developments follows in section 3.3.3.5.

3.3.3.1 Scenario 1: One household – one printer

In this scenario, 3D printers will find their place directly in people's homes. This can be imagined in a similar way as personal computers have evolved over the last decades from only few PCs in the homes of early adopters in the eighties to almost everyone having one from the years 2000 onwards. In the "one household - one printer" scenario, each household will have its own 3D printer which could fulfill their daily needs. Thus, consumers operate the 3D desktop printers themselves and print objects, which they designed themselves or which they downloaded from model marketplaces. As in the case with PCs, the availability of low price printers will be decisive for this scenario becoming reality. As prices drop sharply since important patents expired, this can be interpreted as a signpost pointing into the direction of this scenario. Other signposts would be the increase of printing speed and increasing capabilities of desktop printers as a growing range of printable materials or multi-color options. Another barrier that needs to be overcome for this scenario is the still low usability of available desktop 3D printers.

Figure 5: Schematic visualization of scenario 1: One household – one printer. Source: Own illustration. Icons attributed to the following designers from The Noun Project: User by Doug Cavendish, User by Wilson Joseph, 3D Printer by Bryan Allen, House by Samuel

3.3.3.2 Scenario 2: 3D printing marketplaces

In scenario 2, consumers will mainly be in contact with 3D printing technologies via online 3D printed object marketplaces comparable to the above presented case study. As described in section 3.2.2.3, 3D printed object marketplaces have two groups of users: the designers, who can upload, print and even sell their designs to others and the consumers, who can buy the designs, having them shipped to their location. In comparison to the scenarios 1 and 3, the current one requires less knowledge from the consumers regarding the use of 3D printers and the underlying technologies. Consumers without any prior knowledge could browse offered designs and purchase the 3D printed objects similarly to their behavior in other e-commerce shops. Users with design knowledge can create their own 3D models or customize existing models. Finally, printing the objects would not require any technical knowledge, as everything is “outsourced” to the 3D printed object marketplace (see Figure 6).

Signpost pointing into the direction of this scenario: The possibility to use a wide range of materials will remain to be limited to expensive industrial 3D printers and requirements regarding maintenance will not decrease significantly. Also, if the range of applications will stay limited and thus, the number of objects consumers print by themselves would stay small, it would point into the direction of this scenario.

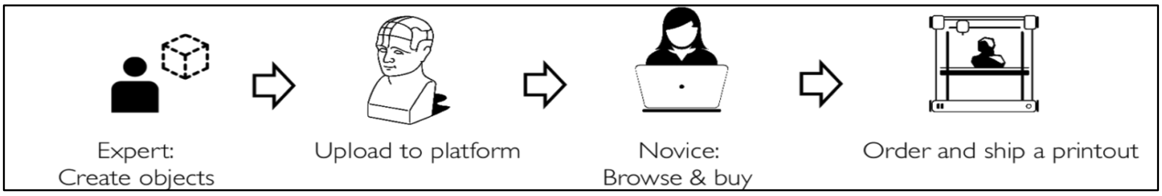

Figure 6: Schematic visualization of scenario 2: 3D printing marketplaces. Source: Own illustration. Icons attributed to the following designers from The Noun Project: User by Doug Cavendish, Statue by Simon Child, User by Wilson Joseph, 3D Printer by Bryan Allen

3.3.3.3 Scenario 3: 3D copy-shop economy

In this scenario, the production of 3D printed objects is dominated by local shops comparable to the classic 2D printing copy-shops. Such shops will provide the hardware, printing materials, and support for consumers. They could also offer additional services as 3D scanning. Customers can receive their object instantly just as today customers take their 2D prints with them from any copy shop (see Figure 7). Shops will charge their customers per object with regard to the actual costs incurring.

Signposts pointing into the direction of this scenario are high maintenance requirements of 3D printers, an increased printing speed as this would allow printing on-demand and thus, it would increase the perceived inconvenience of the shipping duration in scenario 2.

One imaginable business case for this scenario is the provision of spare parts to consumers. Manufacturer could issue the printing job to the nearest 3D printing shop and the consumer can then pick up the spare part at her earliest convenience already within several hours. The manufacturer would not be required to maintain a large stock of all the possible spare parts and thus could minimize storage costs.

Another aspect of this scenario might be that 3D printing shops might lead to local 3D printing communities. In such a setting, people can help each other with the design and operation of the software and technology. In already existing maker hubs in Munich parents sign up their kids for workshops as they think that this will give them an advantage for their professional future.

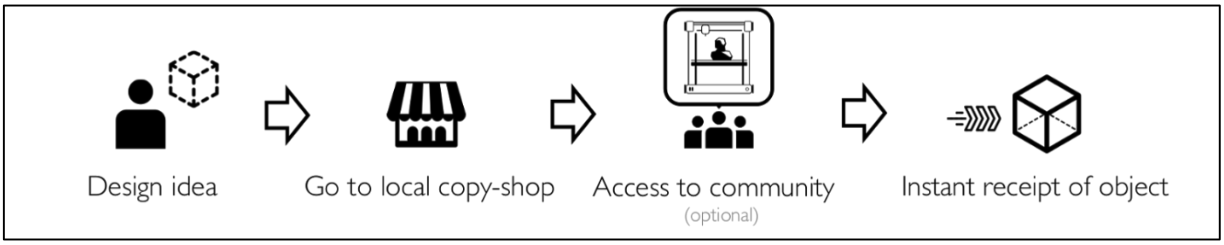

Figure 7: Schematic visualization of scenario 3: 3D Copy-Shop Economy. Source: Own illustration. Icons attributed to the following designers from The Noun Project: User by Doug Cavendish, Geometry by Ilsur Aptukov, Shop by Ahmed Elzahra, Community-Heapth-Advocate by Edward Boatman (edited). Speed by Tim Boelaars, 3D Printer by Bryan Allen

3.3.3.4 Scenario 4: 3D printing behind the scenes

Scenario 4 describes a world in which 3D printing technologies will not be visible to consumers. Instead, Consumers will be provided with more customization options as today for all kinds of products, but it is not important to them how the individualization of their products will be realized technically. Thus, conventional manufacturers will expand their product portfolio, offer more customization options and will use 3D printing technologies in their production. However, consumers will buy the finished products as they are shopping today in stores or via e-commerce shops.

This scenario is probable, if usability of 3D printing technologies cannot be increased significantly, maintenance requirements will and prices for multi-material and multi-color printers stay high. Another signpost pointing into this direction is an ongoing high brand awareness of consumers.

3.3.3.5 Evaluation of the presented scenarios

While companies like Makerbot work for the realization of scenario 1 with their products entering ordinary households, others like Shapeways are instead promoting the path of decentralized creativity with centralized manufacturing (Halperin, 2014). Big names from the industry believe in scenario 1. For instance, Andy Bird, the chairman of Walt Disney International, foresees this scenario: "I think every home within 10 years, probably less than that, will have its own 3D printer, just as many homes now have a 2D or laser printer" (3Ders, 2013a). Others are not as optimistic about the “one household – one printer” scenario. For example an artist, who offers 3D printing workshops in Munich, compared 3D printing with sewing machines: “not everybody has one at home”. In his opinion, 3D printing will be used as a service: either in open spaces or online platforms (interview 11, 2014). The quick growth of 3D object printing marketplaces such as the above presented Shapeways in recent years indicates a high probability of a further development into the direction of scenario 2 in the near-future (see section 3.2.2.3). Further, experts promote the opinion that the topic of 3D printing for consumers is currently hyped and that the future will rather develop into the direction of the scenario ‘3D printing behind the scenes’ (interview 1, 2014).

Different use cases might require different modus operandi as described in the form of the four different scenarios. For example, prints of expensive and seldom used materials such as gold will probably never be produced in low-cost desktop 3D printers designed for household use. With regards to the offered variety of materials, 3D printing copy shops as envisioned in scenario 3 will never be able to compete with more centralized production facilities as described in scenario 2, but will have an advantage in use cases of on-demand-needs with fast-to-print and low-cost materials.

Thus, the emerging field of 3D printing technologies is still in an early phase especially regarding their applications and use cases from the perspective of consumers. The real world in one or two decades from now will certainly not look exactly like one of the presented scenarios, but it will rather be a combination of these and it is not yet clear which one will be dominant.

4. Macro-Environmental Assessment

After the case-based examination of AM technology in chapter 3, the following section puts the topic in a broader context and explores 3D printing from different macro-environmental directions. The structure of this analysis has been derived from the PESTLE-framework with the goal to sketch the role of 3D printing technology in its external environment. Thereby, the assessment comprises mutual influences (i.e. how AM influences and is influenced) between the technology and areas of broader societal interest. Accordingly, the chapter is structured as follows: The first section (4.1) explores in how far 3D printing is supported in different countries by public actors in form of research funds and other activities. Furthermore, the section provides examples of relevant research institutions dealing with AM-related topics in each investigated country. In the second chapter (4.2), thoughts on the economic influences and the market potential of AM technology are discussed. The third section (4.3) consolidates the results of chapter 3 and sums up the impacts 3D printing might have on society. This is followed by a description of the legal framework 3D printing is currently embedded in, with an emphasis on the important area of intellectual property (4.4). The last chapter discusses environmental aspects of 3D printing (4.5). Since technological trends have been exhaustively discussed in the previous chapter, this topic – usually a part of the PESTLE-framework – has been deliberately omitted.

4.1 Public support and research activities

"The technology is coming whether we like it or not" says Michael Weinberg, vice president of the Institute of Emerging Innovation and Public Knowledge and a 3D printing expert (Henn, 2013). Various scholars, for instance Sissons and Thompson (2012), go even further by stating that an economy could benefit enormously from AM technology and generate first mover advantages, if it both supported advancements in fundamental research and managed to establish a well-functioning regulatory framework. Thus, legislators and policy-makers need to acknowledge that they cannot block 3D printing technology, but should rather seek policies, methods and tools to be well equipped for upcoming changes.

Steering the 3D printing ecosystem is, however, a complex endeavor. Scholars argue that key challenges are to regulate the negative effects that 3D printing might have (e.g. in terms of safety and liability issues), as well as to balance the protection of incumbents and patent holders, whilst removing regulatory barriers to innovation and market growth in these areas (Desai & Magliocca, 2013; Osborn, 2013; Lipson & Kurman, 2010; Sisson & Thompson, 2012; Susson, 2013).

Therefore, public policy should actively promote and support 3D printing activities to enable the development of a thriving 3D printing landscape. This includes the funding of fundamental research activities and collaborative research clusters as well as the development of programs that support 3D printing on every societal level (e.g. educational programs, startup funding or industry subsidies) (Lipson & Kurman, 2010; Sisson & Thompson, 2012).

The awareness of the potential of AM is rapidly growing worldwide. Governmental institutions, research institutes and practitioners in various different countries have recognized the need for action and aim to develop AM technologies further. Currently, the USA, the UK and Germany assume leading roles concerning initiating programs for AM research and application. This becomes evident in the number of publications the individual countries issue (Gausemeier, Wall, & Peter, 2013) as well as the total investment the countries appropriate to AM-related research (Dickens, Reeves, & Hague, 2012).

The goal of the following section is to shed light on current practices and public activities in the area of 3D printing across various countries. Therefore, a short profile including general information and a table overview of relevant research institutes of each investigated region or country was developed. The data for the profiles were collected via desk research using the institutes' websites and from information provided in the Direct Manufacturing Research Group's report on the research landscape in Europe (Gausemeier et al., 2013).

4.1.1 Germany

In Germany, AM research is spread across a number of research institutes and universities that have different research foci. From 2003 until 2013, the German Government granted research funding in the amount of 21,2 Mio. Euro to AM-related research activities (Deutscher Bundestag, 2013). The following paragraphs provide examples of leading institutes and research clusters in Germany.

Within the German Fraunhofer-Gesellschaft, the Fraunhofer Alliance Rapid Prototyping unites the competences of 12 institutes in the field of solid freeform fabrication (SFF), which marks the institute's focal point of research (Ader et al., 2004).

At the Fraunhofer Institute for Laser Technology (ILT) in Aachen, extensive work in the field of direct metal laser fabrication is conducted (ILT, 2014). Researchers at the ILT have conceptualized a LENS-type direct metal machine and produced molds in a wide range of metals, as well as industrial parts for aerospace applications. Further, the research team developed the Selective Laser Melting (SLM) process, a variation of SLS that is able to produce completely dense parts (Dickens et al., 2012).

The Fraunhofer Institute for Production Technology (IPT) in Aachen works on combining layered manufacturing with subtractive machining (IPT, 2014). Controlled Metal Build-Up (CMB) has been developed by the IPT and is a LENS-type process that included a machining step after each layer build. Both powder and wire feeds are used. High-speed 3-axis milling is performed after every build step (Dickens et al., 2012).

At the Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM) in Bremen, work is mainly focused on practice-oriented research in Adhesive Bonding Technology and Surfaces as well as Shaping and Functional Materials. The institute's two divisions belong to the largest independent research organizations in Europe.

Besides the coordinated efforts at the Frauhofer institutes, AM research is also conducted at several universities and other organizations in Germany.

The Direct Manufacturing Research Center (DMRC) is a proactive collaboration of key technology suppliers and lead users who have a common interest in advancing AM technologies from Rapid Prototyping to reliable Direct Manufacturing (DM) technologies – meaning, the application of AM in series production (Gausemeier et al., 2013). In 2008, the DMRC was founded and began its work at the University of Paderborn, Germany. Eight professors constitute an interdisciplinary team performing research on the transition of AM towards DM. The federal state of North Rhine-Westphalia and the cooperating companies contributed a total of €11 million for the time frame from 2009 to 2016 to support the research work (Gausemeier et al., 2013).

The Collaborative Research Center 814 Additive Manufacturing is a research center at the University of Erlangen-Nuremberg with a focus on additive production. Under the leadership of Professor Dr.-Ing. Drummer, 35 researchers work on the better understanding of the behavior of powders within the additive manufacturing process. The CRC 814 was established in July 2011 with a budget of €7.3 million and €1.4 million (Universität Duisburg-Essen, 2014) respectively contributed by both the German Research Foundation (DFG) and the federal state of Bavaria (Gausemeier et al., 2013).

The University of Technology in Hamburg-Harburg (TUHH) has established itself as an institution in the fields of teaching of engineering students as well as research and development for scientific and industrial applications. Founded in 2012 at the TUHH, the Institute of Laser and System Technologies (iLAS) has already successfully finished numerous industrial R&D projects in the area of laser material processing (iLAS, 2014).

The main focus of research activities of the Rapid Technology Center (RTC), an initiative established in 2011 at the University of Duisburg-Essen, is working on recent problems regarding the transition from Rapid Prototyping (RP) to Rapid Manufacturing (RM) (RTC, 2014). Prof. Gerd Witt is chairman of the Committee on Rapid Prototyping at the VDI and is an appointed reviewer at the AiF (Arbeitsgemeinschaft industrieller Forschungsvereinigungen) (Gausemeier et al., 2013; Universität Duisburg-Essen, 2014).

Research institutions in Germany

The following list provides an exemplary overview of relevant research institutions in the area of additive manufacturing in Germany. The list does not claim to be complete.

Collaborative Research Center 814 – Additive Manufacturing	
Task Force/ Department / Chair	University of Erlangen-Nuremberg (FAU)
Person Responsible	Prof. Dr.-Ing. Dietmar Drummer Dipl.-Ing. Maximilian Drexler
Short Description	CRC 814 is a collaborative research center for additive manufacturing within the University of Erlangen-Nuremberg. The CRC is 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 cooperates with the Bavarian Laser Center (blz).
Focal Point of Research	Powder bed fusion; build-up rates; material properties; process and part tolerances; design rules; combining processes; software tools; product optimization

Direct Manufacturing Research Center (DMRC)	
Task Force/ Department / Chair	University of Paderborn
Person Responsible	Prof. Dr.-Ing. Hans-Joachim Schmid Dr.-Ing. Eric Klemp
Short Description	The Direct Manufacturing Research Center (DMRC) is a research center of the University of Paderborn and constitutes a proactive collaboration of key technology stakeholders from industry and academia, who have a common interest in advancing Rapid Prototyping technology into dependable, direct manufacturing technology.

	For its research work, the Direct Manufacturing Research Center was awarded as “Ort des Fortschritts” by the Ministry of Innovation, Science and Research of the State of North Rhine Westphalia on 25th November 2011.
Focal Point of Research	Powder bed fusion, material extrusion, build-up rates, manufacturing costs, material properties, process and part tolerances, design rules, product optimization,

Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM)	
Task Force/Department/Chair	Fraunhofer IFAM, Bremen
Person Responsible	Prof. Dr.-Ing. Matthias Busse Prof. Dr. Bernd Mayer
Short Description	The Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM) in Bremen focuses on practice-oriented research in Adhesive Bonding Technology and Surfaces as well as Shaping and Functional Materials. The institute's two divisions, are amongst the largest independent research organizations in Europe. Founded in 1949, the IFAM develops products and processes to the stage of application. The institute is strongly cross-linked within the Fraunhofer Additive Manufacturing Alliance.
Focal Point of Research	Powder bed fusion; material extrusion; binder jetting; manufacturing costs; material properties; process and part tolerances; design rules; combining processes; product optimization; software tools

Fraunhofer Institute for Laser Technology (ILT)	
Task Force/Department/Chair	Fraunhofer IFAM, Bremen
Person Responsible	Dr. rer. nat. Konrad Wissenbach Dr.-Ing. Arnold Gillner
Short Description	The Fraunhofer Institute for Laser Technology (ILT) is worldwide one of the most important development and contract research institutes in the field of laser development and laser application. The activities cover a wide range of areas such as the development of new laser beam sources and components, precise laser based metrology, testing technology and industrial laser processes. This includes laser cutting, caving, drilling, welding and soldering as well as surface treatment, micro processing and rapid manufacturing. The institute won the North Rhine-Westphalia’s 2011 Innovation Award for Additive Manufacturing.
Focal Point of Research	Powder bed fusion; direct energy/metal deposition; build-up rates; build chamber volume; manufacturing costs; material properties; process and part tolerances; design rules; combining processes; product optimization; simulation/thermo analysis

The Institute of Laser and System Technologies (iLAS)	
Task Force/Department/Chair	The Technical University of Hamburg-Harburg
Person Responsible	Prof. Dr.-Ing. C. Emmelmann
Short Description	The University of Technology Hamburg-Harburg (TUHH) has established itself as an institution in the fields of teaching of engineering students, as well as research and development for scientific and industrial applications. The Institute of Laser and System Technologies (iLAS) was founded in 2001 at the TUHH and has already successfully finished several industrial R&D projects in the field of laser material processing. 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, closely cooperate.
Focal Point of Research	Powder bed fusion; direct energy/metal deposition; material properties; process and part tolerances; combining processes; product optimization; new manufacturing technologies

BMBF Digital Photonic Production Research Campus	
Task Force/Department/Chair	Photonics Cluster at RWTH Aachen
Person Responsible	Prof. Dr. rer. nat. Reinhart Poprawe
Short Description	The Photonics Cluster investigates ways to generate, shape and use light, in particular as a tool in industrial production. The "Digital Photonic Production" initiative of an RWTH Aachen University consortium was one of the ten winners out of more than 90 applicants in a national competition of the German Federal Ministry of Education and Research. Companies such as Trumpf GmbH + Co. KG, Jenoptik AG, and EdgeWave GmbH are already involved in the cluster's activities. (
Focal Point of Research	Laser-based rapid manufacturing processes

Rapid Technology Center (RTC)	
Task Force/Department/Chair	Institute for Product Engineering, Faculty of Engineering University Duisburg-Essen
Person Responsible	Prof. Dr.-Ing. habil. Gerd Witt
Short Description	The main focus of research activities of the Rapid Technology Center (RTC) is on recent problems regarding 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).
Focal Point of Research	Powder bed fusion; material extrusion; powder jetting; manufacturing costs; material properties; process and part tolerances; design rules; combining processes; product optimization

4.1.2 The European Union

The European Union has shown organized efforts to make advances in additive manufacturing technologies, as evident in various completed research projects. Already 15 years ago, the European Commission funded a program entitled RAPTIA, which was a European thematic network of research institutions, universities, and industry partners working with rapid tooling (Beaman et al., 2004). After completion, a new seven-year program, NEXTRAMA, the Network of Excellence in Rapid Manufacturing, funded by the European Union's Sixth Framework Program (FP6), followed the project. NEXTRAMA's goal was to achieve efficient and sustainable rapid manufacturing industrial processes through a broadly coordinated effort to create a permanent support organization. Shared work, facilities knowledge, and experience helped define the primary development themes and related research goals. Annual funding levels of over €1.29 million per year were granted to the organization and management of the project (Beaman et al., 2004).

Currently, around 20 active EU FP7 projects include work streams focused on additive manufacturing. The active FP7 projects are worth a combined €99.3 million of public and private sector investment, of which €84 million relate directly to AM aligned work packages (Dickens et al., 2012).

Moreover, the EU has recognized the need for uniform standards and processes in the area of additive manufacturing and initiated the so-called SASAM project, an initiative for Support Action for Standardization in Additive Manufacturing.

SASAM's mission is to drive the growth of AM to efficient and sustainable industrial processes by integrating and coordinating standardization activities for Europe (SASAM, 2014). Further European initiatives such as the European Additive Manufacturing Group (EAMG) have been formed during the past years, laying the basis for the further adoption of AM in Europe (EPMA, 2014).

Also the European Union's 'Horizon 2020' program seeks to support and promote research and innovation in advanced manufacturing and processes. Therefore, MANUFUTURE, an industry lead initiative, was set up in 2004 and launched the European Factories of the Future Research Association (EFFRA) in 2009. Under Horizon 2020, EFFRA aims at encouraging research on production technologies by engaging in a public-private partnership (PPP) with the European Union called 'Factories of the Future'. Research priorities are advanced manufacturing processes, adaptive manufacturing systems, digital factories, human-centered manufacturing and customer-focused manufacturing – topics that also include research on AM technologies (EFFRA, 2014). In addition to the actions taken by EFFRA, AM technologies are considered within the "Key Enabling Technologies" (KETs) of the Horizon 2020 research program.

Besides the coordinated European effort initiated by the European Union, European countries are individually setting up government-academic-industrial centers and programs to support the development of additive manufacturing capabilities.

Within Europe, the United Kingdom strives for the pioneering role in 3D printing research and development activities. This is manifested in the UK's superior financial input to AM research as well as the great number of AM-related research publications (Dickens et al., 2012). Between 2007 and 2016, a total of around €99.8 million has either been invested, or has been committed to be invested in AM research and technology transfer activities. Of this funding, the largest proportion, €31.1 million has come directly from industry, with approximately €16.3 million contributed each by the TSB, EU Framework Programs (FP6 & FP7), and the European Regional Development Fund (ERDF) (Dickens et al., 2012). In the UK, the University of Loughborough's Additive Manufacturing Research Group (AMRG) as well as the University of Nottingham's Additive Manufacturing and 3D Printing Research Group are among the leading centers for AM research and development. There are major research efforts at the University of Sheffield Center for Advanced Additive Manufacturing (AdAM).

Also in the rest of Europe, significant research activities are conducted in various research institutions: Examples are the TNO in the Netherlands, an independent research organization that especially pioneers in the area of food printing; the Institute for Rapid Product Development at ETH Zurich in Switzerland and the Aalto University in Finland. Furthermore, in Belgium, the Product Engineering, Machine Design and Automation Center as well as the Sirris Research Center both belong to the leading institutions in the field of AM-related research.

Research institutions in selected countries of the European Union

The following list provides an overview of relevant research institutions in the area of additive manufacturing in selected countries of the European Union. The list does not claim to be complete.

United Kingdom

Additive Manufacturing Research Group (AMRG)	
Task Force/Department/Chair	School of Mechanical and Manufacturing Engineering, Loughborough University
Person Responsible	Prof. Russell Harris
Short Description	The Additive Manufacturing Research Group (AMRG) at Loughborough University ranks among the worlds‘ leading centers for AM research, development and dissemination. The AMRG is funded by the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing.
Focal Point of Research	Powder bed fusion; polymer vat; material extrusion; binder jetting; material jetting; hybrid; manufacturing costs; material properties; process and part tolerances; design rules; software tools; product optimization

Additive Manufacturing and 3D Printing Research Group	
Task Force/Department/Chair	Faculty of Engineering, The University of Nottingham
Person Responsible	Prof. Richard Hague Ian Ashcroft, Phil Dickens
Short Description	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. The group hosts the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing. Additionally, the Additive Manufacturing and 3D Printing Research Group is the annual host of the International Conference on Additive Manufacturing and 3D Printing.
Focal Point of Research	Powder bed fusion; materials and process development; design-optimization software and business management

Centre for Advanced Additive Manufacturing (AdAM)	
Task Force/Department/Chair	Department of Mechanical Engineering, The University of Sheffield
Person Responsible	Prof. Neil Hopkins
Short Description	The University of Sheffield conducts AM R&D across a wide range of disciplines. AM activity is performed under various 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).
Focal Point of Research	Powder bed fusion; polymer vat; directed energy; binder and material jetting; anchorless SLM; build-up rates; manufacturing costs; material properties; process tolerances; part tolerances; design rules; combining processes; product optimization

Belgium

Sirris	
Task Force/Department/Chair	/
Person Responsible	Thierry Dormal
Short Description	SIRRIS is a Belgian research center for the technological industry. The Center provides innovation and support technology transfer to 2,500 Belgian companies in the sectors of metalworking, plastics, mechanical, electrical and electronic engineering, information and communication technologies. Its activity is split between R&D, information and services. SIRRIS has a European top position in Additive Manufacturing since 1990 with research projects, patents, and 17 AM technologies. In order to provide best support to the industry, SIRRIS has developed networks with national and international science and technology leaders. SIRRIS is very active in setting up new standards for AM technologies during the AM-platform meetings and the SASAM project.

Product engineering, Machine design and Automation (PMA)	
Task Force/Department/Chair	Department of Mechanical Engineering, Catholic University of Leuven
Person Responsible	Prof. Dr. ir. Jean-Pierre Kruth
Short Description	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.
Focal Point of Research	Powder bed fusion; laser re-melting; build-up rates; material properties; process and part tolerance; product optimization; software tools

Finland

Aalto University – Department of Engineering Design and Production	
Task Force/Department/Chair	Aalto University, School of Engineering, Department of Engineering Design and Production
Person Responsible	Professor Petri Kuosmanen
Short Description	The Department of Engineering Design and Production closely cooperates with industry. Long-term scientific research culture with solid know-how of mechanical engineering forms the basics for research and teaching. The Additive Manufacturing Technology group develops new AM applications for industry and for medical use. Medical applications cover a wide range of subjects, from pre-surgical planning models to special and patient-specific tools and surgical implants, and even to tissue engineering and 3D-printing of living cells.

Switzerland

Institute for Rapid Product Development (irpd)	
Task Force/Department/Chair	ETH Zurich
Person Responsible	Prof. Dr. Konrad Wegener Dr. Dieter Woschitz
Short Description	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.
Focal Point of Research	Powder Bed Fusion, Polymer Vat, Build-up rates, Manufacturing Costs, Material Properties, Process Tolerances, Part Tolerances, Design Rules, Combining Processes, Product Optimization

The Netherlands

TNO (Netherlands Organization for Applied Scientific Research)	
Task Force/Department/Chair	/
Person Responsible	Dr. E.R. Meinders
Short Description	TNO is an independent research organization whose expertise and research make an important contribution to the competitiveness of companies and organizations, to the economy and to the quality of society as a whole. TNO has set the goal, in collaboration with partners, of developing AM technique further into a fully-fledged production technique for high tech, high precision and high complexity applications.
Focal Point of Research	Micro stereolithography with highly filled materials; multi-material printing using ink jet technology; metal connections; 3D food printing

4.1.2 The United States of America

In the USA, additive manufacturing receives significant attention from policy and companies. For instance, President Barack Obama emphasized in his 2013 State of the Union address the huge, revolutionary potential he sees in AM technology by changing the way we make almost everything. The White House supports the maker movement and the development of the 3D printing technology not only by providing public attention and financial support, but also by organizing maker fairs on its own. The politics in the US aim to create an environment of tinkerers and makers, which drives this emerging movement in order to create new jobs. In this context, the government supports startups with the program for advanced manufacturing providing entrepreneurs access to more than $5 billion (Shear, 2014).

One of the nation's first publicly funded National Additive Manufacturing Innovation Institute called "America Makes" is located in Youngstown, Ohio (Molitch-Hou, 2014e). It was established in 2012 and is led by the National Center for Defense Manufacturing and Machining (NCDMM) (The White House, 2012). The Institute includes 50 firms, 28 university and research labs, as well as 16 other organizations. The government supports the institute with US-$ 50 million with the aim to increase national manufacturing competiveness and to enhance the adoption of 3D printing technologies and additive manufacturing in the U.S. manufacturing sector (Advanced Manufacturing Portal, 2014). The institute offers multiple events like an International Forum, Technology Shows or 3D Printing Summits (America Makes, 2014).

Another 3D Printing Institute is the Digital Lab in Chicago, Illionois (Molitch-Hou, 2014e). The hub is part of the Manufacturing Technology Program and receives $70 million from the United States Department of Defense (Digitallab 2014).

Firms as well as institutions conduct multiple conferences covering topics around 3D Printing (Stratasys, 2014b; 3D Printing Live, 2014). Furthermore, more than 150 colleges and universities support students in creating things by offering access to 3D printers (The White House, 2014).

Research institutions in the United States

The following list provides an exemplary overview of relevant research institutions in the area of additive manufacturing in the United States. The list is based on Gausemeier et al. (2013) and does not claim to be complete.

Advanced Manufacturing Center (AMC) – Laboratory for Freeform Fabrication (LFF)	
Task Force/ Department / Chair	The University of Texas (Austin), Department of Mechanical Engineering
Person Responsible	Prof. David L. Bourell Dr. Steven P. Nichols, Center Director
Short Description	The Laboratory for Freeform Fabrication (LFF) was already founded in 1988. The build on Carl Deckard's invention of Selective Laser Sintering (SLS), which is one of the first freeform fabrication processes. The LFF is part of the Advanced Manufacturing Center which was established in 2004 to support research in advanced manufacturing and materials processing.
Focal Point of Research	Powder bed fusion (plastic-based, metal-based)

W.M. Keck Center for 3D Innovation	
Task Force/ Department / Chair	W.M. Keck Center for 3D Innovation University of Texas at El Paso
Person Responsible	Prof. Ryan Wicker Francisco Medina
Short Description	The W.M. Keck Center for 3D Innovation is based in the University of Texas at El Paso. With more than $5 million in research funding it is capable of creating three-dim. models in the field of bio-medical, materials and manufacturing research.
Focal Point of Research	Powder Bed Fusion (plastic-based, metal-based); Polymer Vat, Material Extrusion, and Binder Jetting.

4.1.3 The People's Republic of China

China is currently exploring how 3D printing can be integrated into its manufacturing-driven economy. The Beijing-based Asian Manufacturing Association (AMA) is one of the main drivers behind this exploration. Members of the AMA include representatives of China's manufacturing industry, researchers and professors of technological universities, economists and party officials.

In May 2013, the AMA announced plans to found ten 3D printing innovation institutes in China with an initial investment of $ 3.3 million each (Mu 2013).

Also in May 2013, the AMA organized the World 3D Printing Technology Industry Conference, which was attended by 500 representatives of the international 3D printing industry (Ye, 2013). In the course of this conference and in cooperation with international industry and research representatives, Luo Jun, the CEO of the AMA, initiated the foundation of the World 3D Printing Industry Association. Vice Chairmen of this Association include the CEO of German system provider EOS GmbH and Prof. Ian Gibson, author of the book "Additive Manufacturing Technologies". In November 2013, the Belgian system provider Materialise joined the alliance, too (Materialise NV, 2013). Materialise is also the parent company of i.materialise, a 3D printing service provider.

In 2014, the World 3D Printing Industry Alliance hosted the second World 3D Printing Technology Industry Conference in Qingdao, a city in the northern Shangdong province. More than 110 3D printing company representatives attended the event, including companies such as 3D Systems, EOS and Voxeljet (The World 3D Printing Industry Association, 2014). In the course of the conference, the World 3D Printing Industry Alliance together with AMA announced to invest US-$ 6.42 million into a central China 3D Printing Innovation Center and Business Park, which will be stationed in Qingdao. This center is intended as the central platform for coordinating national research on 3D printing as well as its industrial exploitation (China Daily 2014).

Besides industrial additive manufacturing, also the maker movement has arrived in China. As an example, the city of Shanghai is backing 100 so-called maker spaces with up to US-$ 80.000 each. These maker spaces are intended as local platforms of innovation and maker workshops – all of them will feature a 3D printer (The Economist 2013). In Beijing, Shanghai and Shenzhen, there have been first maker fairs. All in all, however, the maker movement in China is still in its beginnings.

R*esearch institutions in the People's Republic of China*

The following tables 11 and 12 provide an overview of relevant research institutions in the area of additive manufacturing in the People's Republic of China. The does not claim to be complete.

Table 11: Key Players China - Industry. Source: Wohlers Associates, 2014

Organization	R&D Focus
Shaanxi Hengtong Intelligent Machine Co., Ltd.	Stereolithography systems
Shanghai Union Technology	Stereolithography systems
Trumpsystem Precision Machinery (TPM)	Laser sintering and laser welding equipment
Delta Micro Factory Corp.	UP! personal 3D printer
Farsoon Hi-Tech Company	Laser sintering systems
Beijing Long Yuan–Automated Fabrication System (AFS)	/
Wuhan Binhu Mechanical & Electrical Co., Ltd.	Machines based on sheet lamination, vat photopolymerization, and powder bed fusion

Table 12: Key Players China - Universities. Source: Anderson, 2013

Organization	Research Focus	Key Researcher
Tsinghua University	Bioprinting	San Yongnian Zhang Renji
Xi'an Jiaotong University, HUST	Bioprinting	Lu Bingheng
Northwestern Polytechnical University (State Key Laboratory on Solidification Processing)	Laser additive manufacturing (LAM)	Huang Weidong
Beijing University of Aeronautics and Astronautics Beijing	LAM	Wang Huaming
Huazhong University of Science and Technology (Fast Manufacturing Center),	drip irrigation parts, bioprinting Selective laser melting	Yu Shengshi

4.2 Economic implications

The global manufacturing industry is under pressure – both to grow and to transform: Firstly, with more and more people entering the global consuming class, experts assume that worldwide consumption will double up to US-$ 64 trillion over the next two decades (McKinsey, 2012). Against this background, forecasts by McKinsey (2012) predict that manufacturing output will continue to grow by about 2.7% annually in advanced economies and 7.4% per year in large developing economies in the same time span. Already today, China is neck-and-neck with America as the world's biggest manufacturer (Markillie, 2012). Additionally, other forces, such as a proliferation of products to meet fragmenting consumer demand and a growing importance of value-added services, urge the manufacturing sector to go through a profound change.

To secure their market power and to match both the increasing and changing demand for consumption goods, global manufacturing companies need to reinvent themselves:

> The new era of manufacturing will be marked by highly agile, networked enterprises that use information and analytics as skillfully as they employ talent and machinery to deliver products and services to diverse global markets. (McKinsey, 2012, p. 1)

This means that manufacturers will no longer succeed by copying and pasting old strategies into new situations, but they must build new capabilities to react to rapidly changing circumstances. In the 21st century, manufacturing companies will establish structures of Cyber-Physical-Systems (CPS) that follow principles of horizontal[3] and vertical[4] integration. They will become increasingly high-tech, from the assembly line to the back office to become more efficient, agile and effective in their procedures. Building up on this hypothesis, the following paragraphs examine the potential role of 3D printing in 21st century manufacturing and related market expectations.

4.2.1 Thoughts on AM microeconomics: The decreasing importance of mass production and complexity

When using conventional manufacturing methods two things are strongly affecting the costs of a produced part: the number of copies of the same part and the complexity of the part's geometry.

The increasingly and massively applied mass production within the last century led to an unprecedented growth in welfare. Through the making of thousands and millions of copies of the exact same products, costs could be decreased tremendously, perfectly harnessing economies of scale. 'Economies of scale' is one of the fundamental principles of modern microeconomics, taught to every economics and business student: the cost per unit decrease with the number of the same units produced. Figure 8 illustrates this relationship schematically using curve 1 for conventional manufacturing methods in a graph with cost per piece on the vertical and the production batch size on the horizontal axis. By building whole machines and

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[3] The "horizontal integration of various IT systems used in different stages of the manufacturing and business planning processes that involve an exchange of materials, energy and information both within a company (e.g. inbound logistics, production, outbound logistics, marketing) and between several different companies (value networks)." (Kagermann et al., 2013, p. 20)

[4] The „vertical integration refers to the integration of the various IT systems at the different hierarchical levels (e.g. the actuator and sensor, control, production management, manufacturing and execution and corporate planning levels) in order to deliver an end-to-end solution." (Kagermann et al., 2013, p. 20)

production lines tailored to manufacture exactly one specific part, the process can be optimized to bring down variable costs to a minimum. The high fix costs diminish per part, if production size is large enough. Even though the principle to distribute the fix costs of expensive machines over a large amount of produced parts is also true for additive manufacturing machines, the important difference is that it is not important to produce only exactly the same parts. The costs stay the same, if you produce many different pieces. Thus, assuming that the machine is used under a high degree of utilization, the cost per piece (more exactly per used material) stay the same, no matter how many of a specific part you produce (displayed as curve 3 in fig. 8) – even if it is only one unique part. This is true only for the manufacturing step – not for the design step.

The second important aspect in conventional manufacturing is the complexity of the produced part's geometry. The more complex a part is, the higher the fixed costs of the designed manufacturing process (see chapter 3.1 for a detailed explanation). Increasing complexity moves curve 1 to curve 2 in figure 8, while with additive manufacturing is independent of the parts' complexities (curve 3).

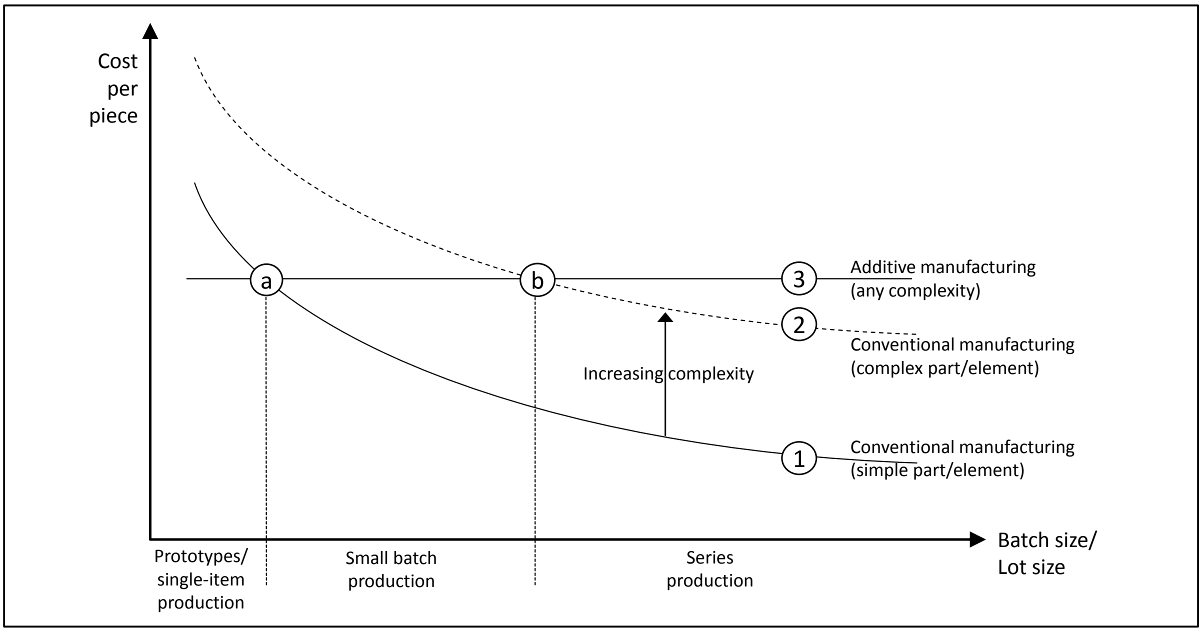


Figure 8: How complexity favors advanced manufacturing over conventional manufacturing methods. Source: Own illustration.

Conventional manufacturing methods will stay the methods of choice for many produced parts in the future. However, advanced manufacturing will develop into an important complementary manufacturing method especially for prototypes and small batch production as well as for complex geometries.

4.2.2 The global 3D printing market and industry growth

Whereas the technology of 3D printing is already about 30 years old, recent developments and innovations have led to a highly dynamic market for 3D printers, related products and services (Raby, 2012; Deagon, 2013).

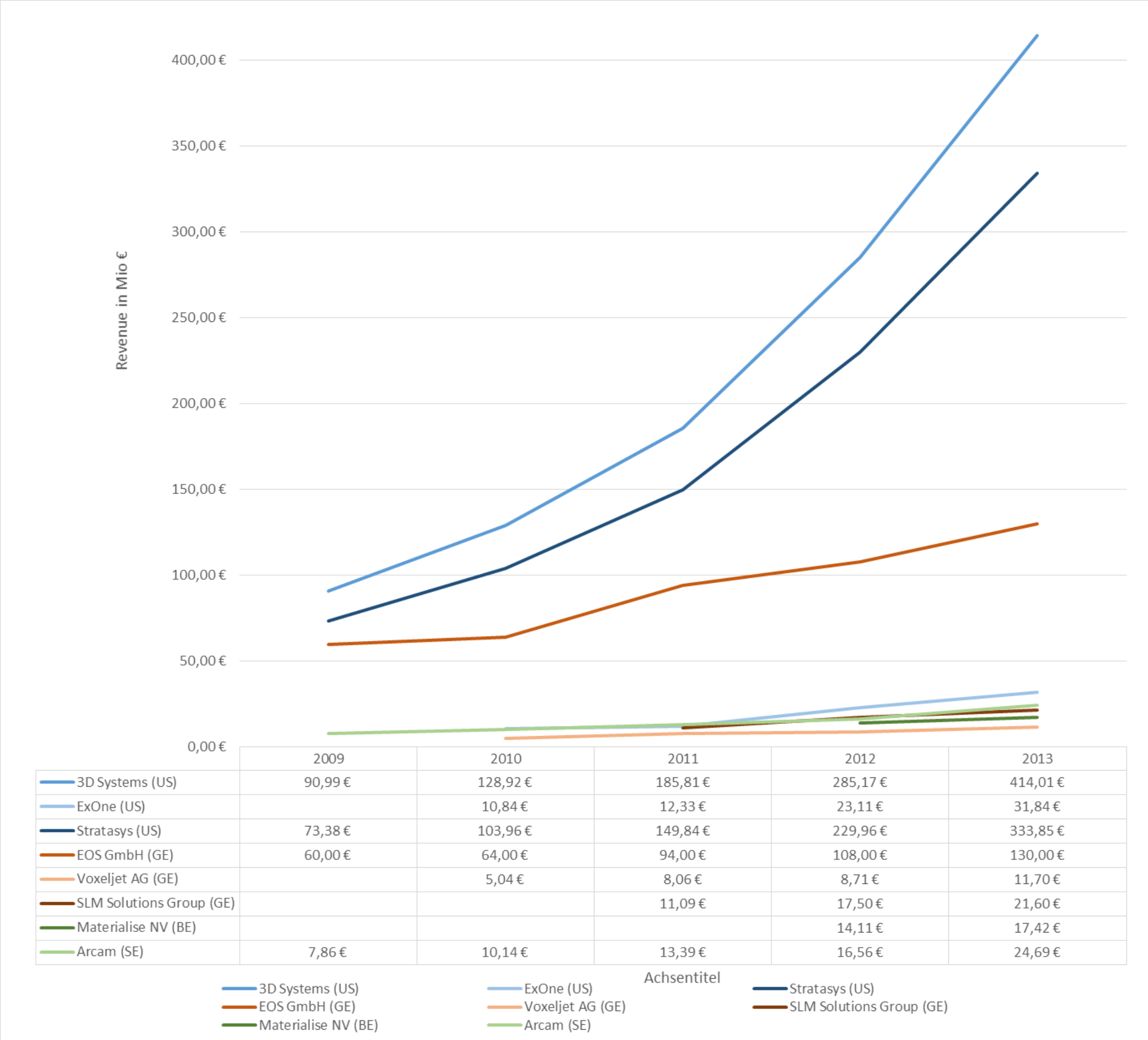
The annual report published by Wohlers Associates Inc., a Colorado-based consulting firm that focusses on trends in the 3D printing industry, is probably the most quoted publication in that area. According to the 2014 Wohlers Report, the global market for 3D printing (including products and services) grew to US-$ 3.07 billion (€ 2.2 billion) in 2013. Looking at the past 17 years, this represents a compound annual growth rate (CAGR) of 34.9 %. In 2012, the global market for 3D printing products and related services grew by 28.6% to US-$ 2.205 billion compared to US-$ 1.714 billion in 2011 (Wohlers Associates, 2013). Over the past 26 years, the average growth rate of global revenues was 27% (Wohlers Associates, 2014).

During the past years, especially the low-cost (< $5000) desktop 3D printer market experienced a tremendous growth with an average of 346% each year from 2008 to 2011. This increase, however, declined significantly in 2012 to about 46.3% (Wohlers Associates, 2013).

Also the metal additive manufacturing market grew by nearly 75.8% in the last 14 years (Wohlers Associates, 2014). This number is based on sales of metal-based AM machines units. 348 of these machines were sold in 2013, compared to 198 in 2012.

It becomes evident that the global 3D printing market is still far from saturated. When looking at specific industry numbers, however, it becomes evident that US firms are still the dominating players. Figure 9 shows a comparison of eight 3D printing companies in terms of revenue growth including three US and three German market leaders.

Despite the impressive growth data during the past decade, the future market potential of 3D printing is a highly discussed topic. Thus, various market research institutions have estimated the size and growth of 3D printing industry in the upcoming years with versatile results. Estimations thereby either tackle the entire global market or focus on specific segments. Table 13 provides some examples of recently published numbers. Even though numbers largely differ, all research institutions agree that the 3D printing industry will continue to grow over the next years due to increasing demand both for industrial applications and in the consumer market



	2009	2010	2011	2012	2013
3D Systems (US)	90,99 €	128,92 €	185,81 €	285,17 €	414,01 €
ExOne (US)		10,84 €	12,33 €	23,11 €	31,84 €
Stratasys (US)	73,38 €	103,96 €	149,84 €	229,96 €	333,85 €
EOS GmbH (GE)	60,00 €	64,00 €	94,00 €	108,00 €	130,00 €
Voxeljet AG (GE)		5,04 €	8,06 €	8,71 €	11,70 €
SLM Solutions Group (GE)			11,09 €	17,50 €	21,60 €
Materialise NV (BE)				14,11 €	17,42 €
Arcam (SE)	7,86 €	10,14 €	13,39 €	16,56 €	24,69 €

Figure 9: Revenues of eight 3D printing companies over the past 5 years. Source: Own illustration.

As regards the German market, Astor et al. (2014) estimate its market share for 3D printing systems, materials and services to be at least 15-20% of the global market. However, to date there are no sound and more differentiated estimations of the German 3D printing market (Astor et al, 2014). Currently, many German companies are in the process of investigating the potential of 3D printing technology for their particular fields of operations. To facilitate knowledge exchange and joined action related to industrial 3D printing, the German engineering association VDMA (Verband Deutscher Maschinen- und Anlagenbau e.V.) initiated a cross-industry platform called the Additive Manufacturing Association in May 2014. Of the 55 members in October 2014 (VDMA, 2014), only 5 companies are primary AM market operators[5] or research institutes (9 members), whereas the largest group (41 members) comprises mainly German medium-sized enterprises in the field of machine and tool manufacturing, robotics or other areas of industrial production.

[5] The *primary* AM market consists of all products and services directly associated with AM processes worldwide. Products include AM systems, system upgrades, materials, and aftermarket products. Services include revenues generated from parts produced

Table 13: 3D printing market estimations. Source: Own research.

3D Printing Market Estimations		
Area	**Estimated growth rate / value**	**Source**
Global 3D printing industry (associated technologies, products and services)	$10.8 billion / €8.4 billion by 2021	Wohlers Associates, 2013
Global 3D printing industry (associated technologies, products and services)	$4.0 biliion / € 3.0 billion by 2025	Research and Markets, 2013
3D printing materials market (including plastics, metals, ceramics, others)	CARG 19.9% until 2018	RnR Market Research, 2014
3D printing for medical applications	$965.5 million by 2019 / € 746,8 million CARG of 15.4%	Transparency Market Research, 2013

4.2.3 The role of 3D printing in 21st century manufacturing

As this report shows, 3D printing will have a wide range of possible application areas in the future, reaching from industrial manufacturing, bioprinting to consumer applications and beyond. The high-tech industry association Bitkom even recognizes that expectations regarding 3D printing technologies have increased in the last year (Bitkom, 2014a). According to a survey among 320 ICT companies in 2014, 76% of the respondents agreed that 3D printing technology is going to cause a significant transformation of certain business areas. Several interview partners (see chapter 5.1.2) also supported this notion. Additionally, 13% of the respondents believe that 3D printing will even have a significant large impact on the economy as a whole. Another study of Bitkom (2014a) states that by today, one-fifth of German citizens (and even every fourth person in the group of 14- to 49-year old people) are interested in using 3D printers to produce products for personal use.

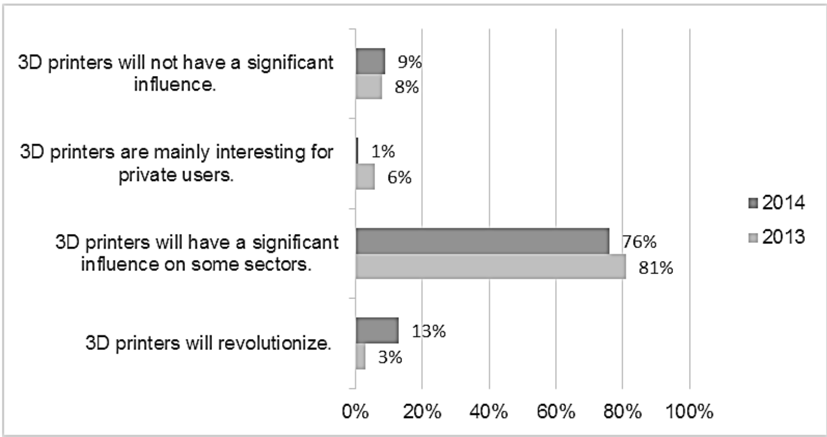


Figure 10: 3D printing expectations. Survey results of Bitkom (2014). Source: Bitkom, 2014b.

To date, the biggest advantage of 3D printing is that a low number of goods can be produced at inexpensive costs compared to traditional manufacturing. This is why the aviation and aerospace industry with relatively small series production is currently the most attractive sector for 3D printing and additive manufacturing procedures (Silva & Rezende, 2013). The fact that a low number of parts can be produced at relatively low prices makes 3D printing also an important technology for prototyping and thus lowers entry barriers for young enterprises. For example, the startup Helico Aerospace Industries used 3D printing in their developing process of an autonomous quadrocopter for filming extreme sports and outdoor activities. According to their founder and CEO Edgar Rozentals, 3D printing accelerated their developing process and saved costs at the same time as it was not necessary to create casting moulds first. He says that AM does not only change the rules for startups, it rather is the entrance card to participate in the game (Kunze, 2014). 3D printing may lead to a new blossoming of the now hardware-based startup scene. For young companies that plan to offer tangible products rather than software only, the new manufacturing technology can be an important enabler.

3D printing in the context of Industry 4.0

Industry 4.0 is a project in the high-tech strategy of the German government that promotes the computerization of German industries on the basis of CPS and the Internet of Things to secure their position as global leaders in the manufacturing equipment sector. In April 2013, the Working Group Industry 4.0 chaired by Dr. Siegfried Dais (Robert Bosch GmbH) and Prof. Dr. Henning Kagermann (acatech) presented their final report at the Hannover Fair. The report entails implementation recommendations to the German federal government.

The Working Group identified eight key areas that need to be tackled for a successful implementation of the Industry 4.0 concept: (1) Standardization and a reference architecture for CPS; (2) new tools for managing complex systems; (3) a comprehensive, reliable and broadband communication infrastructure for industry; (4) deployment of integrated safety and security architectures; (5) deployment of participative work design and lifelong learning measures; (6) training and continuing professional development for employees; (7) adaptation of the regulatory framework in place to adapt to new innovations; and (8) gains in resource productivity and efficiency.

At the same time, experts see a lot of potential in Industry 4.0. If implemented successfully, Industry 4.0 may enable a dynamic configuration of different aspects of business processes, such as quality, time, risk, robustness, price and eco-friendliness. In this way, it can foster optimized decision-making as well as increase resource productivity and efficiency. Industry 4.0 might also create value opportunities through new services, for instance by allowing economically feasible mass customization of products. Finally, Industry 4.0 is seen as a possibility to respond to demographic changes in the workplace by allowing more flexible work organization models of companies, and thus, lead to a high-wage economy that is still competitive.

Reading this list of potential benefits of Industry 4.0, the similarities with 3D printing technology itself become striking. 3D printing is not only tailored to mass customization purposes, but also may significantly contribute to an increase of flexibility, decentralization and resource efficiency in global manufacturing. Thus, 3D printing may become an important enabling technology on Germany’s way towards Industry 4.0. Therefore, notwithstanding the reluctance of certain industry players to adopt 3D printing technologies, a recommendation for further research and development activities in the area seems appropriate.

Exhibit 3: Industry 4.0 and 3D printing. Source: Own research.

Given the transformation of traditional factories towards CPS, industry commentators agree that – to secure their competitive advantage – manufacturers and companies across industries should develop 3D printing capabilities for several reasons: First, 3D printing technology is based on the idea of digitalization of manufacturing and thus seems to fit perfectly in the CPS/Internet of Things area. Second, in times of fast technological progress, 3D printing will help companies to innovate rapidly and continuously, which is an integral ability for economic growth (Deloitte, 2013). Third, with one machine being able to create the entire product, 3D printing can significantly enhance manufacturing efficiency (Hornick & Roland, 2013). There is no need for retooling or assembly and thus, production can be finished in fewer steps. Fourth, if universally applied, 3D printing might also have a significant impact on logistics as consumer products can be locally produced and thus a reduction of transportation activities might become possible (Silva & Rezende, 2013).

Nevertheless, there are also sceptic voices with regard to the potential of 3D printing for industrial purposes in general and large-scale manufacturing in particular. Critics argue that it is highly unlikely that 3D printing can replace the mass production of parts or components in a short to medium time span (Silva & Rezende, 2013). To date, 3D printing is still limited in matching the economies of scale since it simply takes too long to print individual objects to make it cost effective on a sufficiently large scale (Deloitte, 2013; Campbell, Bourell & Gibson, 2012; Susson, 2013). Another crucial issue is the still limited choice of possible feedstock material (Silva & Rezende, 2013).

In sum, the disruptive potential of 3D printing technology should not be underestimated. This notion even becomes stronger when comparing the potential benefits of 3D printing technology with the long-term high-tech strategy of Germany as a global leader in state-of-the-art manufacturing. As exhibit 3 shows, 3D printing can serve as an enabling technology for achieving Germany’s Industry 4.0 vision. Nevertheless, 3D printing is still a technology at the very beginning as regards large-scale and cost-effective manufacturing. A lot of development and research has yet to be done until the technology can compete with traditional manufacturing procedures.

4.3 Societal implications

4.3.1 Mass customization and the development from consumers to prosumers

The possible effects of personal AM technology on company-consumer interactions are manifold. The ability to convert the initial designs of entrepreneurs into feasible products and to give consumers the ability to generate designs according to their own imagination raises customer interaction to a new level (Campbell et al., 2012). That is, desktop 3D printers open up various opportunities for consumer empowerment and ultimately lead to new forms of production and collaboration. Current uses of 3D printing seem to empower consumers in several distinct ways, including: fashioning custom tools to accomplish specific tasks; systems or structures; visualizing problems that are difficult to picture virtually, expressing aesthetic taste, individualism, and, of course, having fun by making personalized toys (Ratto & Lee, 2012).

Alongside this empowerment, considerable shifts in consumer behavior can be observed. Today, consumers increasingly wish for individualized experiences and expect that products to be tailored to their specific needs (Ratto & Lee, 2012). The newly emerging modes of customization are mainly consumer-driven. The *prosumer* (Ritzer & Jurgenson, 2010) is a model that puts the consumer at the heart of product innovation. Now, facilitated by digital desktop fabrication, prosumer modes of production are "traversing from the digital to the material" (Ratto & Lee, 2012). One of the described production modes constitutes mass customization. *Mass customization* describes the approach of using industrial rapid prototyping technologies, not just for a small batch of test pieces, but to manufacture end-products with customer-specified features (Ratto & Lee, 2012). With desktop 3D printers, consumers can design and produce new products easily themselves – tailored exactly to meet their particular needs.

A popular example is the NIKEiD. Nike's Web site allows users to design customized shoes with individualized color combinations and personal text insignia (Nike, 2014). This form of manufacturing is thus able to introduce elements of individual tailoring to products normally associated with mass production, but at mitigated price points due to economies of scale.

Also, so-called co-creation platforms are distinct types of mass customization that provide prosumers with the opportunity to interactively personalize products. End users can download a certain basic design file from an online database, the specifications of which they then alter to their distinct wills. Hence, the role of the customer has been elevated from a passive recipient of "expert" designs to the active originator of design innovation (Campbell et al., 2012).

As the boundaries between digital and physical production become increasingly blurry, so too do traditional conceptions of labor (Ratto & Lee, 2012). "Commons-based peer production" (Benkler, 2006), which is enabled by digital networks, has proven transformative in the digital world by introducing modes of production of large projects (Linux, Wikipedia, etc.) based on collaboration and the widely distributed contributions by many, as opposed to mass production from a centralized source. Hence, 3D printing may act as a catalyst for cloud manufacturing in networks of decentralized manufacturing firms (Lipson & Kurman, 2013).

Not only does 3D printing allow for decentralized production, but it also promotes the division and distribution of labor. While traditionally the processes of product idea, design and manufacturing were done by the same entity, 3D printing allows and even encourages splitting the work. Designers and manufacturers do not necessarily have to be part of the same entity anymore, nor do they have to know each other personally. This way of working opens up new opportunities spurring product innovation.

4.3.2 Maker movement

While additive manufacturing technologies have already gained a strong position in the industrial sector, the development in the consumer market is still at an early stage. So far, the technology lacks an application that makes owning a 3D printer indispensible to private persons. Lipson & Kurman (2013) compare the current consumer-level 3D printing technologies to the "Altair phase", meaning the personal computer in the 1970s. Back then, the first personal computers were clumsy do-it-yourself kits that were targeted at technically skilled users. The mainstream adoption of personal computers was only triggered by applications like email, search engines and instant messaging services that quickly emerged around the rise of the Internet. These applications created new markets, new business models and attracted millions of new users to the personal computer. The absence of that particular application for 3D printers, a so-called "killer app" (Lipson & Kurman, 2013, p.39), is the reason why the average consumer and small business has not yet felt the need to purchase a 3D printer for home or office use. It is yet unclear if there will be such an application for consumer 3D printers in the future and what it will be. 3D printing is not yet a household technology, but it is taking its first steps into mainstream as a growing number of early adopters familiarizes with the technology and owns a 3D printer in their homes. Most of these early adopters are so-called *makers*. Makers can be compared to power users for software companies. Similar to hackers who like to alter software to their will, *Makers* bend technology to their will (Lipson & Kurman, 2013, p. 48). Although nobody really knows where the term *makers* came from, it is widely used and even named a whole movement – the *maker movement*. According to interviewee 13, three key drivers have fueled the maker movement and led to the status quo. These include the access to digital production capacities, the availability of affordable, easy to operate 3D design software, and the broad establishment of maker-to-consumer platforms. The maker movement is a celebration of the increasingly popular do-it-yourself innovation and spans all kinds of different technologies, not just 3D printing (Lipson & Kurman, 2013).

4.3.3 3D printing for sustainable development in developing countries

4.3.3.1 Promoting self-directed sustainable development

Applying 3D printing technology in developing countries could have a significant social impact, as it shows potential to promote economic self-sufficiency and to provide a better quality of life and education. Inequality in human development is a major global issue. The Human Development Index (HDI) is a measure along three dimensions: “life expectancy, educational attainment and command over the resources needed for a decent living” (United Nations Development Programme, 2013, p. 1). It indicates that 46 out of 186 rated countries are ranked as “Low Human Development” countries, showing the inequality in development and quality of life.

Pearce et al. (2010) state that “of the methods of sustainable development that have been most successful at enabling the impoverished to pull themselves out of poverty are those that favor egalitarian, local, small scale, people centered, bottom-up, peer-to-peer methodologies, which directly support AT [appropriate technology] paradigms” (p. 18). AT is a term for those technologies that can be used easily and economically from readily available resources by local communities to meet their needs by simultaneously complying with environmental, cultural, economic, and educational resource constraints of the local community. This idea represents the logic of *self-directed sustainable development* meaning that habitants of developing countries can take the initiative to produce goods from first necessity and to act proactively towards their goals, instead of depending on the help from other countries and institutions.

The potential of 3D printing technology for fostering self-directed sustainable development is mostly dependent on three factors: First, the broad availability and application of such *open-source appropriate technology* (OSAT) (Garrett, 2014). Second, the increasing number of free CAD models for various objects, especially for households (Pearce et al., 2010), and their availability on the internet. And third, the introduction of self-replicating 3D printers like RepRap and Fab@home, which can also replicate expensive equipment at much less cost.

If these criteria are met, several scientists share the opinion that 3D printing technology has the potential to change business models, shift production locations and shorten supply chains (Garrett, 2014). According to Garrett (2014), these changes are especially relevant for developing countries. 3D printing as OSAT can minimize the fixed costs and volume necessities associated with low cost manufacturing. This will result in lower entry barriers for the manufacturing of many goods (Kohn, 2014), resulting in less dependency on other more cost-competitive countries. Moreover, it can open doors for local startups, since volume is not any longer the main driver to reach low production costs. By providing the chance to implement fast new ideas and products using mainly e-waste and recycled material, 3D printing offers entrepreneurially thinking people in developing countries the means to develop and materialize their ideas. This entrepreneurial spirit has also evolved with the help of organizations like FabLab, which aim to encourage young people and teach them how to use this technology (FutureMag, 2014).

The main potential for this low-cost customized production can be found in rural communities, which are partially isolated from the rest of the country due to underdeveloped infrastructure (3Ders.org, 2013d). By providing each of these communities with a 3D printer and the knowledge how to use it, they are given the chance to be independent and to cover their basic needs, e.g. by printing their own clothes (Turk, 2014), kitchenware or toilets (Nichols, 2013). This might make African countries self-efficient and independent from import and other countries’ help (Hajustin.com, 2013).

4.3.3.2 Access to education and healthcare supplies

As regards education, computers in developing countries' schools are often still a rarity (Merlin, 2014). To ensure high-skilled education and increase employment opportunities, it is thus important that pupils can be equipped with cheap tools. Due to 3D printers, experimentation with parts that are usually too fragile or expensive for experimentation might become possible. For example, files of fossils can already be downloaded and printed for free for experimentation in schools. The financial burden for schools in developing countries can further be reduced by providing cheap 3D printers like the W.AFATET, a model that was entirely created from recycled e-waste material, while the electronics and the motor only cost $100 (Naramore, 2014).

Furthermore, with 3D printing it can become possible to produce objects for people who lack basic amenities (such as toiletries or rain buckets) or who are in need for cheap healthcare supplies. This can for instance be of significant benefit for people in countries of war, who have been seriously injured and who are limited in their everyday life. An exemplary project that addresses this issue via the use of 3D printing is *Project Daniel* which promotes the use of 3D printers to make prosthetic arms for children of war in South Sudan (3ders.org, 2014a). 3D printing allows printing prostheses for only US-$ 100 and within six hours. Even though the functionality of printed prostheses is still limited compared to high-cost prostheses, the technology allows children of war to do basic things like feeding themselves or using a computer again (Bort, 2014).

4.4 Legal framework conditions and regulatory challenges

The emergence of 3D printing technology and its broad dissemination due to falling costs of machines and materials (both in the industrial and private area) might create a range of new issues in the legal landscape. Osborn (2013) states that "some of [these issues] are straightforward applications of existing law, whereas others require careful thought to balance competing policies and develop legal mechanisms" (p. 7). Relevant literature indicates that there are two key developments brought about by 3D printing that could have a significant influence on law in general and intellectual property law in particular: First, 3D printing enables an easy and cheap way of reproducing physical objects by printing them from computer files (Sissons & Thompson, 2012). Thus, commercial trading and sales could switch from certain objects to the underlying design files (Hornick & Roland, 2013; Osborn, 2013). Secondly, the 3D printing movement is based on an open-source ethos with a large amount of lay people collaboratively participating in the development and exchange of product files (Sissons & Thompson, 2012). Both developments raise important questions regarding the legal status of 3D printed objects and ask for new regulation modes of 3D printing activities. The following sections outline different legal and regulatory areas that could be affected by 3D printing.

4.4.1 Aspects of intellectual property and patent law

Many possible decisions of intellectual property (IP) law in 3D printing are yet to be explored and decided, which implies that the laws' content and interpretation are highly dynamical. Therefore, also the range of plausible scenarios is extensive. On the one side, von Hippel (2005) claims that legislation and regulations that is specifically tailored to support user innovation will lead to a relatively higher social welfare. On the other side, the business research firm Gartner (2013b) estimates that by 2018 intellectual property theft caused by 3D printing might lead to a loss of $ 100 billion worldwide.

In this section, the focus stays on copyright, utility patents, design rights and trademarks as the most important IP concepts with regard to 3D printing. Moreover, state-of-the-art licensing models and approaches for enforcing IP are presented. We deliberately exclude the discussion on the status of 3D files with regard to copyrights and patents. This is currently a very hypothetical discussion and likely to be solved by case law. The publication by Weinberg (2013) provides a good introduction to the inherent issues.

4.4.1.1 Copyright in 3D Printing

Copyright is an unregistered right that protects mainly artistic and creative works that are fixed in a tangible medium without protecting the idea that the work expresses (Weinberg, 2010). Every work that is created and fulfills the requirements for copyright protection is automatically protected until 70 years after the author's death (US & Germany). In contrast to patents, copyright recognizes independent creation of the same work by two authors given that they did not copy from each other. Examples in 3D printing that are likely to have copyright are sculptures, figures or jewelry (Weinberg, 2013).

With respect to the distribution of media files over the internet, in US copyright law, the so-called *fair use doctrine* legalizes certain otherwise infringing actions, for instance the use of protected material for academic purposes, parody or news reporting. However, the exact boundaries of this exception are hard to foresee and depend on the case.

Another important reform was the *Digital Millennium Copyright Act* (DMCA). One aspect of DCMA allows online-sites with shared content, such as Youtube, Flickr or 3D printing communities, to be not directly liable for their users' uploads. Instead, they act as an intermediary between the copyright holder and the infringing user. Whenever a copyright infringement is claimed, the original author can request the site to take the material in question down (the so called DMCA takedown-notice). After the site has done so, it informs the uploader who has the possibility to challenge this takedown using his legal rights (Häfeli, 2014).

In 2011, the 3D printing community experienced their first DMCA takedown-notice. A discussion of this incident can be found in "Printing the impossible triangle" by Rideout (2011).

4.4.1.2 Patents in 3D printing

Patents are a protection right for novel, non-obvious inventions. This right must be granted by the respective patent office after the inventor has applied for it. After examination, a patent is granted for 20 years and the resulting strength of protection is generally higher than that given by copyright. Firstly, the right holder receives absolute blocking rights. This means that he can enforce his rights regardless whether the infringing entity did not know about the patent or developed the same invention independently (anti-ignorance protection). Secondly, he is not only protected against direct infringement, but also can enforce his right against contributory infringement (interview 16, 2014).

Although patents appear to be an interesting way to protect 3D printed inventions by individuals, this idea involves some challenges in practice. Most importantly, patent law is a highly complex subject. Determining whether an invention is indeed suitable for being patented and then filed in the formally correct manner, requires usually an expensive mandate by a patent attorney. Furthermore, the patent application and the research require a mid-sized upfront investment.

While being the inventor will only apply to a small group of end-users, most of them will experience patent law from the perspective of the entity, who produces objects, which are protected by another entity. With 3D printing the (potential) costs of patent infringement may decrease significantly since the replication process of objects becomes technologically easier as well as cheaper (Desai & Magliocca, 2010; Hornick & Roland, 2013). This is especially important for the US where (in opposite to the EU) the personal use is not excluded from the patent protection. Due to the aforementioned anti-ignorance protection, the patent rights are also enforceable if the end user did not know about the patent.

To face the patent challenges brought about by 3D printing, Professor Hod Lipson of Cornell University has suggested a system of micropatents (Lipson, 2012). Such micro-patents would provide small businesses and individual inventors with a smaller IP "unit" that is both less expensive and quicker to produce. Lipson describes such a system as follows:

> An inventor would submit, for a few hundred dollars, a document describing his invention to a centralized government micro-patent repository. The document would be time-stamped and then immediately released to the public. Its lifespan would be shorter — perhaps five years rather than the traditional 20 — and only for demonstrated fields of use. In order to prevent patent trolling, it would protect only objects being sold commercially. Like a patent, it would cover a utilitarian application. Like a copyright, it would be easy and straightforward to obtain and would be tested only upon dispute. By filing a micro-patent document, the inventor would be granted an immediate, implicit, short-term exclusive right to the disclosed idea, and only in case of a dispute by two *practicing* commercial entities would the case be evaluated. (Lipson, 2012)

4.4.1.3 Design protection and trademarks

Besides copyright and patents, design patents (US) or design rights (EU) are another important part of modern intellectual property rights. They are used to protect the appearance of handcrafted and industrial products in order to prevent competitors to use the design for their own products. Similar to patents, design protection requires the subject matter to fulfill certain requirements with regard to novelty and non-obviousness. Furthermore, registered design protection provides the holder with absolute blocking rights as well (Häfeli, 2014).

Trademark law aims at protecting customers from confusion about the origin of products. This protection right requires registration by the owner of the sign (e.g. a brand logo) that is to be protected and valid as long as the sign is used. The law against unfair competition provides automatic protection, but is in general more limited (Häfeli, 2014).

3D printing gives individuals the ability to produce a remarkable range of fake-trademarked goods in privacy. In this way, 3D printing could bring piracy into the home. According to Osborn (2013), the question hereby is, in how far 3D printing will influence the two distinctive rationales of trademark law, namely “consumer protection” and “producer incentives”. Bradshaw et al. (2010) argue that it is not necessarily a trademark infringement, if a specific item (e.g. the narrow-wasted Coca-Cola bottle) is used for private purposes since the traditional consumer confusion about the source of the object will not be an issue. This will, however, raise new and difficult questions about the proper role of regulation for brand names and related items (Osborn, 2013). Susson (2013) recognizes that duplications of initially trademarketed objects could easily circumvent trademark protections by simply producing the items without a logo.

4.4.1.4 Licensing

The holder of an IP protection right is free to license his work to others under custom conditions. This also includes the choice to not give any modification, distribution or similar rights to anyone, as it is common with industrial products. However, in the maker movement, authors usually allow others to creatively work with their creations.

In order to prevent potential users from dealing with complex licenses for every single item and make licensing things easier for the creator, public copyright licenses have been invented. They allow users to recognize directly which rights they can practice and save the inventor from setting up his own legally valid license. The most popular public license for digital works is

Creative Commons (Creative Commons, 2014), which comes in several variants that give a set of permissions from the author to the licensees. They all include the right of the licensee to distribute and display the work. However, the author might choose to require that he is mentioned in an adequately manner (BY) or that the work may only be used non-commercially (NC). Furthermore, he can choose that all derivative work is shared under the same license (share-alike: SA) or deny the licensee to modify the work (non-derivs: ND).

The enforcement of IP rights in practice is challenging as digital files can be reproduced without loss of quality and, furthermore, the control of the end-users' devices is limited. Currently, the main enforcement solutions are (a) to print objects via a trusted service or (b) to directly stream to the printer. Both approaches limit the user in customizing and improving the original design. This kind of enforcement of IP rights for digital products is known from the music and film industry as *Digital Right Management* (DRM).

One example for the former approach (a) is Shapeways. Shapeways is both shopping platform for the user and the trusted printing service for the final product. The IP rights of the designers are enforced by giving the end-customer no access to the design files, but rather directly shipping only the final product.

The later approach (b) is implemented by solutions of Authenise[6], Secure 3D [7]and FabSecure[8]. An article by the British Broadcasting Corporation (BBC, 2013) has referred to them as the "Spotify for 3D printing". They enforce the designers copyright by directly streaming data to the printer in a low-level format. For the end-user it is then difficult to reverse-engineer the original CAD file from the transmitted control commands.

In both cases, the IP infringers might scan and reprint the final object. Nevertheless, this circumvention will never create design files of the same quality level as the original one, especially when it comes to fragile structures.

4.4.1.5 Emerging Issues

The interviewed expert (interview 16, 2014) described a possible strong increase on copyrights as one major challenge:

> One idea is that, if the [maker movement] will grow and if more people will be creative, this will of course lead to many more copyrights being created and thus more unregistered design rights – not on the files, but on the designs of objects. It is very important to keep these two things apart. And if these designs of objects come into the scope of copyright, and many people do that, we will have a large increase – maybe even explosion – of copyright in subject matter. That whole thing could lead to a market where you don't know anymore what's protected, whom you have to license with. [The most evident solution is] [...] to make it more difficult to get rights by, for instance, excluding functional items more thoroughly from copyright protection, because that's really not where they belong.

[6] http://www.authentise.com/

[7] http://secured3d.com/

[8] http://www.fabsecure.com

Another approach is to introduce some kind of collective licensing organization. These collective licensing organizations would save the individual from having to research the right holder for every single object. However, the interviewee states:

> [...] the major problem is to limit this somehow. In case of copyrights, you know quite well who the authors are and who aren't. Furthermore, most songs are protected by copyright. There, it is easy to get into copyright, because the uncertainty whether something is protected by copyright comes into place again. Many people will probably register for your collecting society, but they may not even have proper copyrights or proper design rights.

As patents are examined more carefully, this would not be a problem. However, petty patents, as they are less carefully examined, are a problem again.

From a corporate perspective, the lack of clarity with regard to intellectual property and 3D printing causes concerns regarding an increasing danger of product piracy when using AM technologies and the associated CAD software. By sending the files from company to customer, computer to 3D printer and from persons to persons, the probability of data leakage increases. The fear of losing intellectual property (IP) and thus important competitive advantages to other players might decrease the overall willingness to adopt the AM technologies in industry. During expert interviews this concern was evaluated as well. On the other hand, products are already being copied today without using AM (interview 4, 2014). Therefore, it is questionable if a large-scale introduction of AM is really likely to change something in this area. Interviewee 17 (2014) supports this opinion, warning not to make irrational decisions. He sees the need for clearer IP rights by no means connected to the AM development. He agrees that every information that is highly sensitive to a company and has disastrous potential when it leaks, needs to be protected. But in his opinion this is neither something new nor restricted to CAD data. This also accounts for finance data just as much as for CAD data (interview 17, 2014). IP rights as a whole have to be adapted to the digital age by the government to protect industries, but also customers.

In conclusion, the major upcoming issues in IP policies with regard to 3D printing for the end-user and the related consequences for industry players are undefined situations in copyright on files, the hurdle of enforcing licenses in absence of clear IP policies and the possible “explosion” of IP rights.

4.4.2 Aspects of standardization and consumer protection

4.4.2.1 Environmental law and quality standards

In the area of environmental law, two challenges with regard to 3D printing could be identified: First, there might be a need for environmental product and quality standards regarding the environmental impacts of 3D printing, such as norms for printers, legal limits for emissions due to toxic fumes or feedstock powders and standards for filaments (Osborn, 2013). Second, if 3D printers will become a mainstream global production methods, new regulatory mechanisms regarding the holistic environmental impact of 3D printing will be required (Osborn, 2013).

4.4.2.2 Issues of product liability

As stated above, the 3D printing movement has been built on an open-source ethos with many DIYers participating in the market (Sissons & Thompson, 2012; Osborn, 2013). This can on the one hand lead to a vast amount of innovations, but there is also a risk that lay people unintentionally create shoddy and dangerous products. Consequently, certain questions of product liability arise.

The first one raises the issue of the legal status of a CAD file. To apply strict products liability law, CAD files need to be considered as "products" in the legal sense. However, their legal status has not been clearly defined yet. According to Osborn (2013), the ongoing discussion is similar to the question whether computer software should count as "products" (and thus fall under products liability law) or merely as "services" (and thus not) [9]. As aforementioned, this discussion is highly controversial and will most likely be solved by case law.

The second question tackles the issue of liability in case a buyer or consumer is injured by a product printed from a CAD file. Even if treated as "products", strict product liability can only be applied to people "engaged in the business of selling or otherwise distributing products"[10]. In the case of 3D printing, however, it is likely that many people will give away CAD files for free and therefore cannot be held responsible under strict products liability. In addition, the boundaries between "professional merchants" and "casual sellers" need to be redefined in the 3D printing scene. Amateur sellers might not be as sophisticated and careful about their design as professionals. Nevertheless, a one-time, casually uploaded CAD file could go viral and sell millions of copies (Osborn, 2013). Another related issue concerns the liability of professional 3D printing services. It has to be discussed in how far a 3D printing service can be sued under strict products liability in case a 3D printed product injures a customer. It is unlikely that a 3D printing service, which merely prints out CAD files on behalf of customers, knows as much about the products sold as traditional manufacturers. Osborn (2013) assumes that strict products liability does not apply in this case since 3D printing services are more akin to service providers than to manufacturers.

4.4.2.3 Issues of certification and product approval

Another hurdle that is keeping many firms from adopting 3D technologies today are admissions and lengthy certification procedures for different material and parts that have been produced and processed by 3D Printing machines, especially in the area of aerospace. Both interviewee 2 and interviewee 12 stressed that right now, entrance barriers for these technologies are so high that small and medium sized companies can hardly afford them. The admissions are very costly as there are no standards yet. Thus, the companies have to run numerous tests with different materials, to find out how the material, e.g. titanium, is reacting with different AM methods and get them finally admitted, before they can manufacture a single piece for serial production. These lengthy processes not only hinder innovation among big corporations, most of all they

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[9] In the area of products liability and software, many discussion focus on whether the software has a greater *service* aspect (as in the case of custommade, customer-specific programs) or *product* aspect (such as massmarketed software). The same distinction could apply to CAD files (Osborn, 2013).

[10] Restatement (third) of torts: Prods. Liab. $1

prevent adoption and thus competition in the market, which inhibit overall innovation in the field of 3D technologies (interview 2, 2014). The certification system thus has to prioritize these technologies higher and shorten the time until materials and production methods get admitted. The government has to support small and medium sized companies the foster wide spread adoption of 3D Printing technologies (Gausemeier et al., 2012).

4.5 Environmental assessment of 3D printing

In 2000, Nobel Prize winner Paul Crutzen coined the term *Anthropocene* to describe the emergence of an era in which the influence of human behavior on the Earth's atmosphere and ecosystems has become so significant that it constitutes a new geological epoch (Crutzen & Stoermer, 2000). Already today, "humanity uses the equivalent of 1.5 planets to provide the resources we use and absorb our waste" (Global Footprint Network, 2013). Until 2050, the world's population is expected to increase from 6.9 to more than 9 billion – with the majority of this growth happening in urban areas of the developing and emerging world (WBCSD, 2010; PWC, 2012; FAO, 2009) and about 800 million people joining the socio-economic middle-class (WBCSD, 2010). Furthermore, in 2009, the number of people living in urban areas has surpassed the number of people living in rural areas for the first time. Thereby, more than one in every seven human beings lives in an urban slum.

Global developments like world population growth, demographic change and urbanization lead to a continuously increasing demand for consumer goods in the next decades (PWC, 2012). As long as business-as-usual methods remain, however, higher rates of production will automatically come along with a further increase of environmental degradation due to resource consumption and emissions (FAO; 2009; WBCSD, 2010). Against this background, the urgency for a fundamental change of material use and production procedures becomes evident.

Both in mass media and scientific literature, it has been argued that additive manufacturing bears a significant environmental sustainability potential by reducing the material waste and transportation-induced CO_2-emissions related to 3D-printed products (Huang et al., 2013). This notion is explored in the following section that qualitatively summarizes the environmental impacts of 3D printing, systemized along the typical product life cycle stages of a cradle-to-grave life cycle assessment for evaluation industrial systems (EPA, 2006).

4.5.1 Raw materials acquisition and inbound logistics

Materials used in AM processes influence the demand for specific sets of raw materials. Thereby, one of the main issues are the costs and availability of filament for thermoplastic extrusion procedures. For example, industrial plastic polymers (such as ABS) are often made from non-renewable petrochemicals (Hammond & Jones 2008; American Chemistry Council, 2014). Despite the introduction of new naturally based materials such as PLA, Birtchnell et al. (2013) raise concerns about the environmental impacts:

> About 2 per cent of global oil is used to make a wide variety of manufactured goods in a rainbow of different polymers and as much as 95 per cent of packaging and bottling worldwide is derived from oil products. 3D printing in many low-end machines relies on ABS, which is a polymer

> derived from oil, or in some cases corn ethanol derived PLA, which generally requires oil-based fertilizers anyway. (p. 7)

Nevertheless, 3D printing can reduce the amount of raw materials required in the supply chain. 3D printing manufacturing processes follow an additive production logic and thus only use the material that the final object requires (Reeves, 2009, p. 5; Wagner, 2010). This effect, however, is currently moderated by material waste caused further down the product life cycle by the depreciation of critical material properties (Silva & Rezende 2009, p.2).

Regarding inbound logistics questions, such as the storage, movement, and distribution of raw material and mid-process parts, there is broad consensus that additive manufacturing contributes greatly to a lean supply chain[11]. First, additive manufacturing is often used to manufacture structurally complex end products in one production step. By rendering intermediate steps, such as tooling, molding and casting, (partially) obsolete, 3D printing helps to save not only materials and energy, but also CO_2-emissions traditionally generated during the transportation of the mid-parts (Reeves, 2009, pp. 5-6; Huang et al., 2013, p. 1197; Silva & Rezende, 2013, p.278). However, this positive impact is limited by the fact that direct (i.e. end-product) manufacturing applications of 3D printing still make up below one third of all applications (Wohlers Report, 2013). With 16% of additive manufacturing applications being in the indirect production domain (i.e. casting, tooling) (Wohlers Report, 2013), the waste creation by the precision industry leaves much room for improvement (Drizo & Pegna, 2006). Furthermore, while distributed hyper-local manufacturing at the site of the consumer would indeed minimize CO_2-emissions from end-product distribution, it would require the continuous distribution of production materials to end-consumers instead. Thus, it might just shift CO_2-emissions from one transport activity to another (Silva & Rezende, 2013, p. 281).

4.5.2 Manufacturing

Product manufacturing is probably the most often cited environmental advantage of 3D printing. Some scientists suggest that the technology can significantly reduce material and possibly energy consumption (Choudhury, 2013; Huang et al., 2013). However, insights on this topic are still highly dependent on the specific shape of the printed product, the manufacturing machine type and its utilization (Faludi, 2013).

4.5.2.1 Material Consumption Impact

3D printing techniques enable net shape manufacturing where the initial production of the item is already very close to its final form, thereby reducing material waste as well as the need for surface finishing (Jacobs, 1996; Grimm, 2002, Dove, 2003; Drizo & Pegna, 2006; Goodrich, 2013; Kurman & Lipson, 2013). According to some research, it even has the potential to reduce material costs by 90% (Choudhury, 2013). For example, a life-cycle analysis of selected additive manufacturing applications in the scale model kit industry conducted by Nopparat et al. (2012) showed that 3D printing produces 62.4% less material waste than typical injection molding systems. It has been acknowledged that AM has particularly strong material-efficiency potential in industries with high material waste, such as aerospace where for each 1 kg of end-

[11] A paradigm in supply chain management, which encompasses the idea of reducing waste throughout the supply chain (Tuck & Hague, 2006, p. 364; Huang, 2013, pp. 1197 f.; White & Lynskey, 2013, p.2).

product 19 kg are wasted (Reeves, 2009). Furthermore, 3D printing as a design and mass-customization enabling instrument can be used to validate the market acceptance of new products. It can thereby reduce the waste stream in further product development stages and eventually waste accumulation from mass-produced unsuccessful product innovations (Schroeder, 2001; Stier & Brown, 2001; Drizo & Pegna, 2006).

The new forms of material waste inherent to some AM processes moderate this positive effect, however. First, 3D printing often requires support structures that can be recycled only to a limited extent (Choudhury, 2013; Silva & Rezende, 2013). Second, heating degradation of plastic powder materials used in powder bed 3D printing processes can cause substantial inefficiencies (Wagner, 2010; Kurman & Lipson, 2013; Silva & Rezende, 2013). In a polymer laser sintering process for instance, at least 30% of the powder-based material can end up being unusable (Silva & Rezende, 2013). Third, home 3D printers can lead to material waste due to print failure rates that can reach 20% (Wittbrodt et al., 2013). Thereby, inkjet 3D printers can deem 40-45% of the plastic ink unrecyclable (Faludi, 2013). Finally yet importantly, additive manufacturing can cause material waste through a flood of trial productions (Drizo & Pegna, 2006; Kurman & Lipson, 2013). Nevertheless, the overall impact of 3D printing on typical material consumption in the production process seems to be highly beneficial.

4.5.2.2 Energy Consumption Impact

The energy consumption of 3D printing processes cannot yet be clearly evaluated. On the one hand, some studies cite significant energy consumption advantages for low volume production badges when compared to conventional techniques (Goodrich, 2013; Nopparat et al., 2013). Energy costs could be cut by 50% thanks to AM using energy only to transform materials enough to be used once. In comparison, traditional processes, such as metal milling, need energy to transform the raw material first into a block of bulk, then to mill it and eventually to recycle the big amount of produced chips into a new block (Silva & Rezende, 2013). In line with these insights, Nopparat et al. (2013) note that most of the energy used in AM is to create the final product, while injection molding only uses a fraction of the total energy to produce the final product.

On the other hand, energy-thirsty and badly utilized industrial 3D printing machines are still a major factor for a high energy-inefficiency of additive manufacturing (Choudhury, 2013; Huang et al., 2013). Some studies report using heat or a laser to melt plastic consumed an estimated 50 to 100 times more electrical energy than injection molding to make an object of the same weight (Kurman & Lipson, 2013). Furthermore, the operating procedure for 3D printers, i.e. equipment warm-up and cool-down stages, has a critical impact on energy use (Huang et al., 2013).

Independent of the inconclusive research on energy consumption of additive manufacturing, a strongly moderating role for its overall environmental impact play the energy sources. Products made using solar-powered 3D printers, for example, can drive down the environmental impact even further (Goodrich 2013). In the future, agile 3D printing facilities powered with set amounts of stored renewable energy could rapidly adjust fabrication rates to the level of available renewable power. Thereby they could reduce the negative energy-consumption impact for 3D printing even for larger production badges (Kurman & Lipson, 2013).

4.5.2.3 Toxicity Impact

Overall, the pollution of terrestrial, aquatic, and atmospheric systems through 3D printing seems to be lower than through conventional manufacturing processes (Huang et al., 2013). A main contributing factor for this positive impact is the omitted usage of cutting fluids, which are typical in other manufacturing methods and the main source of hazard in production waste streams (Huang et al., 2013).

However, toxicity and environmental impacts of 3D printing materials and chemical solvents used for their removal is often still not entirely clear. Potential toxicological health and environmental risks can occur from handling certain materials during product manufacturing (Drizo & Pegna, 2006). Moreover, the operational processes of home 3D printers have been shown to produce potentially carcinogenic ultra-fine particles in high quantities. Particularly harmful are the secondhand printing fumes that contain toxic byproducts given off when plastic is heated to high temperatures (Stephens et al., 2013).

4.5.3 Outbound logistics

As stated, AM offers possibilities for leaner supply chains with regard to outbound logistics. The transportation ways are shorter or even nonexistent. As the overriding costs are machines and raw materials, production can take place at a home 3D printer and thus requires no packaging and warehousing. (Huang et al., 2013, p. 1196-1197; Kurman & Lipson, 2013; Silva & Rezende, 2013, p. 6). Also custom parts produced in small batches, such as rarely used spare parts for cars and aircrafts, can be manufactured close to the point of demand (Loughborough University, 2009). No transportation means a smaller carbon footprint. Even if transportation is necessary, additive manufacturing opens new possibilities in terms of design, such as hollow structures, so the weight of the product and its carbon footprint can be decreased (Kurman & Lipson, 2013).

Green building already has a significant eco-potential, but it would further benefit from sustainable outbound logistics with 3D printing. A D-Shape 3D printer is potentially capable of printing a two-story building on site, and requires only ordinary sand and an inorganic binder. Earlier tests have shown results that are indistinguishable from marble and its durability is highly superior to that of masonry and reinforced concrete and uses very low levels of energy as compared to traditional manufacturing processes (Belezina, 2012; DeFreitas, 2012).

4.5.4 Product use, re-use and maintenance

The usage of a product is an important step in its life cycle as it is a multiplier of the entire environmental footprint. The longer a product is used the lower is the relative impact of prior stages of the value chain. For a greener lifecycle, the design of a product should therefore aim for a customized product that fits its user, with a better operational performance and improve product longevity, i.e. extend the useful life of a product and therefore its reduce its impact on the environment (Diegel, 2010, p. 69).

AM opens new possibilities in product design, so that products can provide better functionality: CAD designs help improve the form, function, performance and durability (Kurman & Lipson, 2013). The quality of components exposed to high thermal loads can be greatly enhanced by conformal cooling as temperature spreads more evenly, in contrast to conventional straight drilled cooling channels that could not follow the cavity contour (Hsu, 2013). Fully optimized geometries can be made significantly lighter in weight, leading to massive savings during the use of the product. AM enables the production of components 50 per cent lighter than conventionally manufactured (Wagner, 2010). Lighter parts result in tremendous savings in fuel, and thus less CO2 is released into the atmosphere (Loughborough University, 2009). Car manufacturers like Bentley Motors hope to make their luxury, heavy-weight automobiles lighter in order to meet strict emissions regulations, but the impact is even greater for aerospace components. While the impact in the aviation industry is greatest, it is true for many products that carbon savings during the use of products make up for more than just the energy required to produce them. (Wagner, 2010).

AM furthermore enables the production of customized products. Diegel (2010) suggests that products which are so well designed that they become lasting objects of desire, pleasure and attachment, are less likely to be disposed of – and thus more sustainable. Diegel gives the example that a sports car like the E-type Jaguar can be more sustainable than a hybrid car because it is cherished by its owner, well-maintained and performs superbly in the complete life-cycle, possibly lasting multiple generations (p. 3).

On the other hand, there is a downside to home-printed products. There is close to no quality control for CAD models and no research on durability of such products, which could possibly produce more waste and material to recycle. As Diegel (2010) points out, there is even very little research deals with design quality from the point of view of sustainable design.

4.5.5 Recycling and Waste Manufacturing

There is already a massive waste problem when it comes to plastic, and this problem could increase with additive manufacturing. First off, distributed manufacturing makes it possible and convenient to print a plastic item at a low cost, and second off, cheap home 3D printers have a high failure rate (Lomas, 2001) which results in more waste and more recycling issues.

In order to recycle bad prints and convert waste plastic into filament, there have been several efforts to create domestic plastic extrusion systems such as the open-source RecycleBot (Baechler et al., 2013). More typically though, the material properties of a product are corrupted and cannot be reused. A greener solution is using the corn-based plastic called PLA that is biodegradable and a better alternative to petroleum-based plastics (Goodrich, 2013; Kurman & Lipson, 2013). Many producers of materials recommend incineration and landfill as a method of waste disposal, even though there is no data on the biodegradability and possible leaching from landfills (Vantico, 2003). Some substances detrimental to environment have been found among decomposition products (e.g. carbon oxide, carbon dioxide, and oxides of nitrogen, among others) (Drizo & Pegna 2006, p. 66). In addition, the potential toxicological health and environmental risks from handling, using and disposal of additive manufacturing materials are unknown. Some "older generation" materials containing epoxy resins have proved to cause severe eye and skin irritation and allergies (Drizo & Pegna, 2006, p. 66). This part of the life-cycle analysis requires further research in order to evaluate the whole environmental impact of additive manufacturing.

4.5.6 Final evaluation

When speaking about the environmental impact of additive manufacturing, it has often been pointed out that it bears a significant *potential* for reducing negative impacts. As the literature review shows, the actual influence is, however, highly dependent on the specific use case.

In summary, 3D printing bears potential for a strong positive environmental impact throughout the whole product life cycle. First, allowing for more efficient material use and relying more heavily on materials from renewable sources, it can reduce harmful mining activities. Moreover, 3D enables one-step manufacturing and thereby limits the wasteful material and energy impact of typical pre-production processes and transportation. It can greatly increase material efficiency during production and facilitate a leaner supply chain for distributed manufacturing that saves energy for warehousing and reduces CO_2-emissions for transportation. Furthermore, by enabling mass-customization and design superiority, 3D printing can extend product lifetimes and thereby reduce waste. Lastly, biodegradable materials can reduce harmful recycling and material mining, while new recycle bots even open the door to a true cradle-to-cradle product life cycle.

To fully realize these potentials, however, policy makers have to boost research and innovation on material toxicity topics and ensure proper recycling and disposal methods. Second, the use and invention of new biodegradable materials as well as the avoidance of rapid garbage generation through home and industrial printing should be incentivized. Finally yet importantly, the introduction of energy-efficient printing machines and generation of more renewable energy is needed to ensure the economic sustainability of 3D printing as well as higher technology adoption that would allow for more use of the environmental benefits.

5. Conclusion and Recommendations

5.1 3D Printing – A promising field, but not (yet) a game changer

Some researchers and industry commentators have argued that 3D printing could be the next emerging general purpose technology with the potential to inflame a new round of creative destruction in the Schumpeterian sense and to lay the foundation for the next industrial revolution (e.g. Anderson, 2012; Markillie, 2012; Tien, 2012; Barnatt, 2013; Heathcote & Roux, 2012). The overarching goal of this study was to examine 3D printing technology in a holistic way and to critically evaluate its potential and possible impacts on state-of-art practices. Therefore, a comprehensive, qualitative assessment of the technology was conducted. After an introduction to additive manufacturing technology as such, the exploration started with a detailed analysis of different 3D printing applications (chapter 3). Afterwards, the findings of chapter 3 have been put into broader context. In a macro-environmental assessment, 3D printing technology was explored from different directions (chapter 4). This part of the study focused on mutual influences between the technology and areas of societal interest. Finally, the goal of the following chapter is to summarize findings and to draw a final conclusion on the future potential of 3D printing technology.

5.1.1 Expanding the toolbox

In the course of this study, various technical opportunities and challenges related to AM processes were elucidated in each area of investigation. The findings are summarized in table 14. It becomes clear that AM has a range of advantages compared to conventional production processes. Especially new degrees of freedom in product and process design open up opportunities for increased part complexity, material savings and weight reduction. Furthermore, the direct connection between digital part design and manufacturing allows leaner production chains and enables mass customization at no or little additional costs. At this point in time, however, these opportunities are still moderated by various technical challenges that need to be overcome to make AM applicable for mainstream mass production purposes. Thereby, a major hurdle lies in the availability of appropriate printing materials in both the industrial and the healthcare sector. The amount to choose from is still limited, and the printed quality, which typically requires post-processing, is in some cases inferior to conventionally produced items. Also in the consumer market, a broad dissemination of 3D printers is still hindered due to technical challenges. Many desktop printers are still slow, require expensive printing material and deliver insufficient printing quality. However, considering the speed of development in the desktop 3D printing market, it is likely that the quality of the devices will keep on increasing in the near future.

Table 14: Opportunities and challenges of AM technology. Source: Own research.

Area	Advantages and Opportunities	Challenges
AM for industrial applications	• New degrees of freedom and geometries in product and process design (e.g. bionic designs) ○ Components of products can designed differently (e.g. to decrease the number of single parts) ○ Increased part complexity possible without significant increase in production costs ○ Weight reduction due to new design possibilities • Increase in product development speed • Material savings due to additive production logic • Reducing assembly efforts as well as cooling and cycle times in part production • Possibilities of (mass) customization at no or only little additional costs • Digitalization of manufacturing process allows leaner production chains	• Choice of materials still rather limited • Little amount of digital materials on the market yet • Printed parts often require post-processing procedures • Depending on AM technology, a lot of printing material is wasted (e.g. when involving sand) • Production of extremely large parts (e.g. pipelines) not yet possible due to limited printer size • AM cannot reach economies of scale as easily as manufacturing methods • Available CAD-software is often not capable of capturing the full spectrum of AM design possibilities • Certification and approval of 3D printed parts and products still a complicated and cumbersome process
AM in the healthcare and well-being sectort	• Cost-efficient development of individualized solutions (e.g. surgical guides, implants, prostheses) • Adding a third dimension to so-far two-dimensional processes of tissue engineering • Possibility of printing biocompatible materials • 3D food printing to produce artificial food for people with swallowing problems	• Limited choice of materials • 3D printing technology has to be adapted (e.g. smaller resolutions) • 3D bioprinting still at the stage of fundamental research • 3D food printing still at the stage of fundamental research
AM in the consumer market	• Speed of desktop 3D printers increases with every new generation • Falling prices of hardware • With expiring patents, new desktop printers join the market and open up the spectrum (FDM, SLS, stereolithography) • Constant advancements in software • Possibility of printing a plethora of different items (functional items, entertainment items, customized items, specialized items)	• Materials widely limited to plastics • Materials often offered as expensive proprietary equipment by printer manufacturers • Printing of larger items is time consuming • Quality of printed objects often not good enough for daily use • No general quality standards

Notwithstanding the technical challenges, if successfully applied, AM technology might have a direct impact on state-of-the-art practices in both industry and the consumer market. Figure 11 provides a brief summary of direct impacts, AM related trends and the investigated use cases.

In the industrial area, AM is already an established manufacturing method in some sectors and has been used for over 30 years – so far predominantly for parts production and tooling. Recent R&D advancements, however, have triggered two major trends: (1) an advancement from rapid prototyping to rapid manufacturing, and (2) a facilitation of mass customization of end-products. In this way, AM technology can be used for new purposes and finally enters the stage of end-product manufacturing. Thus, in the long-term, AM technology may change the relationship between producers and consumers significantly. From a corporate perspective, mass customization is about the process of matching customer expectations with the company's competences. As Tien (2012) observes, this means that traditional manufacturers will have to enhance their competencies as service providers: "When mass customization occurs, it is difficult to say whether a service or good is being delivered; that is, a uniquely fitted shoe can be considered to be a co-produced service and good – a 'servgood' product" (Tien, 2012, p. 290).

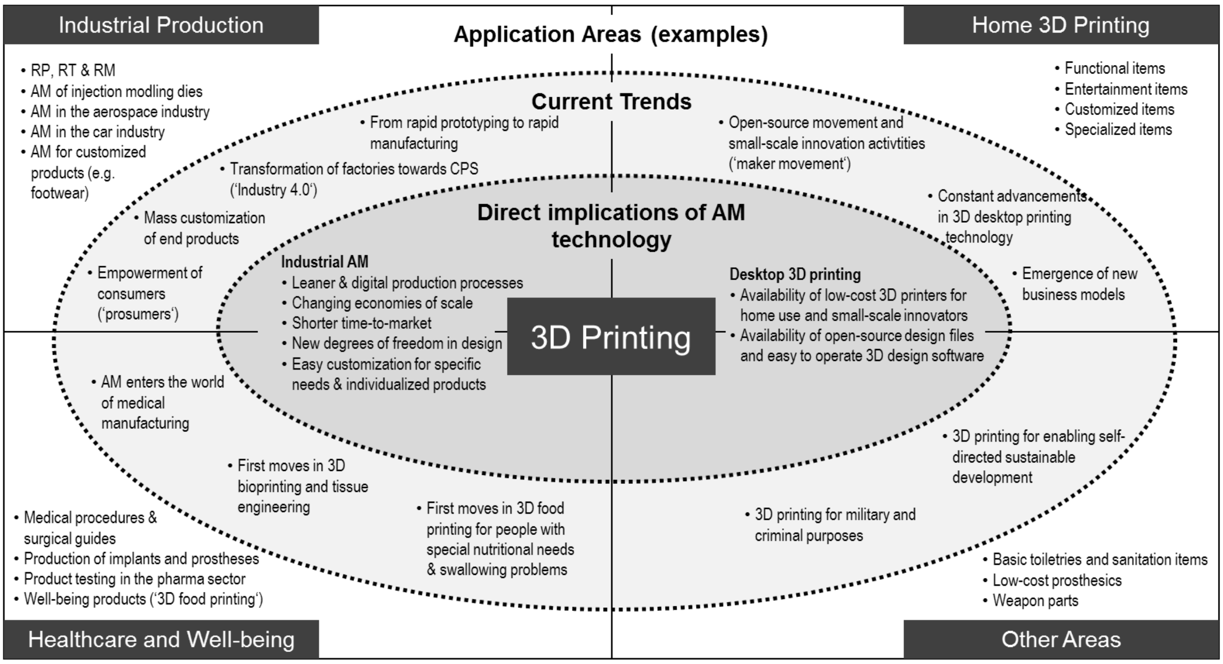

Figure 11: Implications, trends and application areas of AM technology. Source: Own research.

Apart from modes of mass customization, AM – especially when applied as rapid manufacturing – might also serve as an enabling technology for digital manufacturing. This becomes particularly interesting when looking at the German vision of an Industry 4.0. Companies increasingly start to establish structures of Cyber-Physical-Systems and try to digitalize their processes as far as possible. With its flexibility, AM technology has the potential to become an essential tool in the CPS arena. Nevertheless, there are also sceptic voices as regards the potential of 3D printing for industrial purposes in general and large-scale manufacturing in particular. Critics argue that it is highly unlikely that 3D printing can replace the mass production of parts or components in a short to medium time span due to remaining technical challenges.

This study identified cost-efficient and uncomplicated product individualization as one of the major advantages of AM technology. This aspect becomes particularly striking when looking at the healthcare sector. There, individualized design, for instance for surgical guides, implants, prostheses, orthoses or tissues, is probably more needed than in any other application area. Therefore, the interviewed experts agreed that in the healthcare sector, 3D printing bears probably the highest potential for a fundamental market disruption. Akin to all other AM areas, however, 3D printing applications vary in terms of technological maturity in the field of healthcare, too. Whereas 3D printing is already common practice in dentistry, 3D bioprinting of tissues and living cells is still at a stage of fundamental research and far from practical application. The same counts for 3D food printing, a topic that mainly gained recognition due to playful applications like the printing of cakes or pasta with special design pattern. Nevertheless, in the long-term, food printing could be used for creating artificial food for people with swallowing problems or special nutritional needs. In this way, 3D food printing might contribute to a higher quality of life for certain target groups.

The latest development in 3D printing, which also inflamed the recent hype around the topic, is certainly desktop 3D printing. With the expiration of relevant patents, a plethora of different desktop 3D printers was brought to market. With the technology becoming faster, more reliable and cheaper, the low-cost personal 3D printer market experienced a tremendous growth in the last years. This development coincides with improving design capabilities that enable advances in computer hardware and software, as well as an improving ability of individual users to combine and coordinate their innovation-related efforts via internet. In other words, during the past years, it got continuously easier for consumers to get what they want by designing products for themselves – a development that inflamed the so-called *maker movement*. The maker movement is strongly dedicated to local, collaborative and community-based inventions. Thus, scholars argue that 3D printing brings about the advent of home-based product printing, which might trigger the development of a more design-oriented economy as a potential successor to the information economy (Easton, 2009). The earlier-mentioned tremendous market growth in the area of desktop 3D printers and the vast amount of open-source design and file sharing platforms for 3D models as well as the physical objects, such as Thingiverse or Shapeways, could be seen as first indicators for these hypotheses.

Nevertheless, to date, makers remain a comparably small niche and the future development of home 3D printing is far from certain. Only the next years will reveal in how far individual behavior of a critical mass of people will be changed by 3D printing. As stated, this is mainly dependent on technical advancements in home 3D printing. Hardware manufacturers, however, have recognized deficiencies and have begun to develop desktop models with significantly bigger chamber sizes (Stratasys, 2014a).

Bringing the three fields – AM for industrial production, healthcare and in the consumer market – together, the macro-environmental revealed that the market for AM technology and related services is far from being saturated and offers significant financial potential in the future, both for Germany and on a global scale. Furthermore, it is likely that AM could also positively contribute to other important pillars of society: first, to society by empowering people and consumers around the globe and thereby contributing to the field of sustainable human development; and second, to environmental protection by mainly offering possibilities for emissions savings and waste reduction along the life-cycle of products. Nevertheless, it became also evident that some of the main factors that currently impede a broader dissemination and adoption of 3D printing technology, are located in the legal and regulatory area. There are many open questions in this field, reaching from issues of intellectual property to complicated procedures for part approval. Thus, to enable a thriving 3D printing landscape, these regulatory challenges need to be overcome in order to set the right boundary conditions. For a summary of the macro-environmental assessment, see table 15.

Table 15: Summary of macro-environmental assessment. Source: Own research.

Macro-Environmental Assessment of AM	
Public support & research activities	**Germany** • Research activities at several universities, research institutions and corporations. • Research mainly in the field of industrial applications, AM technology, mass customization and materials • No overarching research program other than on EU level
	European Union • 20 EU FP7 work streams focused on AM (combined value: €99.3 million) • SASAM project for AM standardization • European Working Group EMAG • Pioneering role: Great Britain with so far around €99.3 million investments in AM research
	USA • The National Network for Manufacturing Innovation (NNMI) • National Additive Manufacturing Innovation Institute in Youngstown, Ohio (US-$50 million public support) with 94 member consortium to drive AM progress and 20 collaborative research projects • Digital Manufacturing and Design Innovation Institute in Chicago, Illinois (US-$70 million federal investment) • US-$ 5.0 billion public funding for manufacturing startups
	China • Asian Manufacturing Association (AMA) announced to establish10 3D printing innovation institutes in China with initial funding of US-$3.3 million each • City of Shanghai substitutes 100 maker spaces with US-$ 80.000 each
Economic expectations	**Global market** • Global market reached volume of US-$ 3.07 billion in 2013 • Future global market expectations vary; Wohlers Associates estimate US-$ 10.8 billion by 2021 • Over the past 26 years, the average growth rate of global revenues was 27% • Desktop 3D printing market grew annually on average by 346% from 2008 to 2011 • Metal AM market grew by nearly 75.8% in the last 14 years
	German market • German 3D printing market is estimated to be 15-20% of global market • 3D printing could serve as enabling technology for Industry 4.0 • New market opportunities for German companies in all areas
Legal and regulatory impacts	**Current issues** • Open questions with regard to intellectual property (copyright, patents, trademarks and licensing • No quality standards and norms for 3D-printed products in the consumer market • Complicated procedures of product approval and certification
	Need for new (trans-)national modes of regulation • Modes for standardization and product approval both in the industrial and end-user AM market required • New tools in IP (e.g. micro-patents, new licensing opportunities) required • Environmental standards required
Societal implications	**From consumer to prosumer** • Consumer empowerment • Possibility of mass customization • Shift in consumer-producer relationships
	An emerging maker movement • Increasing dissemination of desktop 3D printers • Increasing group of home & DIY innovators and small-scale producers
	3D printing in developing countries • 3D printing to enable self-directed sustainable development • Access to education and healthcare supplies
Environmental impacts	**Possible positive impacts** • Reduction of amount of raw material due to higher material efficiency • Lighter products result in CO2 emission savings • Leaner supply chains due to automised production and less transportation • Omission of certain materials might reduce pollution • New design possibilities can enhance durability of products
	Possible negative impacts • Printing materials are often toxic and based on petrochemicals • Limited recycling opportunities might increase waste • Printing process is energy-consuming • Particulate emissions due to printing processes

5.1.2 3D printing: Quo vadis?

This report has shown multiple perspectives on the future of 3D printing that highly differed depending on the area of interest. In industrial AM, experts agreed that AM technologies are not a fundamentally disruptive, yet promising new production tool that might have the potential to significantly influence certain industry branches. In contrast to that, in the healthcare sector – and especially in the area of 3D bioprinting – AM methods provide truly disruptive potential. The most uncertain future, however, is the role of 3D printing in the consumer market. There, opinions highly vary and at this point in time no clear statement can be made. Therefore, four different scenarios have been developed that can serve as a basis for further investigations. Figure 14 at the end of this chapter depicts a summary of these future scenarios as derived from the study at hand. Furthermore, as displayed in exhibit 4, this evaluation also reflects the opinions of the interviewed experts.

To put it in a nutshell, even though 3D printing may not inflame the next industrial revolution, it is definitely an important manufacturing technology that can have a huge impact on certain sectors. This notion even becomes stronger when comparing the potential benefits of AM with the long-term high-tech strategy of Germany as a global leader in industry and manufacturing.

Perspectives on 3D printing

"I would not compare 3D printing to the internet or the steam-engine or something like that. Rather compare it for example with a CNC (Computerized Numerical Control) milling machine. These computer-controlled machines basically also brought more flexibility and more possibilities in construction without revolutionizing the whole world of production. (...) Bioprinting would really have the potential to develop into a real revolution. But this is a totally separated topic from industrial 3D printing in my view: First, it is still in the phase of fundamental research and second, the actors are totally different from those in the industrial 3D printing area."

Interviewee 1

„I think that particularly in the area of medical applications – be it 3D printing for medical manufacturing or 3D bioprinting with biological materials– 3D printing and additive manufacturing technologies bear a significant disruptive potential. Individualized design is probably more needed here than in any other application area."

Interviewee 7

"I think that in future you cannot ignore this technology. In certain areas, additive manufacturing is a substitution technology, but on the whole it is a supplemental technology, which offers the possibility to build totally new construction parts and also business models. (...) There is the risk that at the moment the topic is extremely hyped and that today's promises will not be kept. (...) If this is a revolution – that is something others should decide. (...) I think it is definitely an important technology and I think you make a mistake if you do not intensely deal with this topic"

Interviewee 12

"There is a conglomerate of new technologies and developments such as digital factories, decentralized manufacturing and new business models. 3D printing is a tiny element thereof and the current hype is not justified. (...) 3D printing is another method for primary shaping and manufacturing, which has advantages and disadvantages over conventional methods. You have to minimize the disadvantages and utilize the advantages - that is the usual thing with new technologies. It may develop further and gain more importance, but at the moment its impact is minimal. Thus, in my opinion it will have only marginal macro-economic effects. Only if the whole maker movement gains momentum and drives a certain societal transformation: if people increasingly value individualization and the recoupment of sovereignty over their own products, because they can repair most devices themselves, then this would mean a huge influence. However, this would be a social trend of our time, which is somehow independent of the advanced manufacturing technology."

Interviewee 10 [focus of the interview was the plastic material market]

Exhibit 4: Perspectives on 3D printing: Quotes from the expert interviews. Source. Own research.

It is likely that AM will strongly influence the mechanical engineering, automotive, aerospace and medical engineering industries, which are all of high importance for Germany. Furthermore, upcoming fields like 3D bioprinting offer opportunities to establish new fields of expertise and global leadership. Thus, especially for Germany the topic of 3D printing is of very high relevance and has a tremendous potential.

The international comparison of AM research activities and public funding around the world showed, however, that in Germany public support of AM technology is not as strong as in other countries. Especially the USA and China aim for a pioneering role in that area and have adopted large budgets for research activities, innovation and startup funding. Thereby, both nations do not only focus on AM for industrial applications, but also specifically support the arising maker movement by fostering the establishment of public maker spaces and facilitating access to the technology.

To secure its competitive advantage as the world's leading high-tech nation, Germany should promote AM technology and ensure public support for research and innovation programs that go beyond EU programs. Therefore, 10 policy recommendations have been formulated that can serve as a basis for further proceedings.

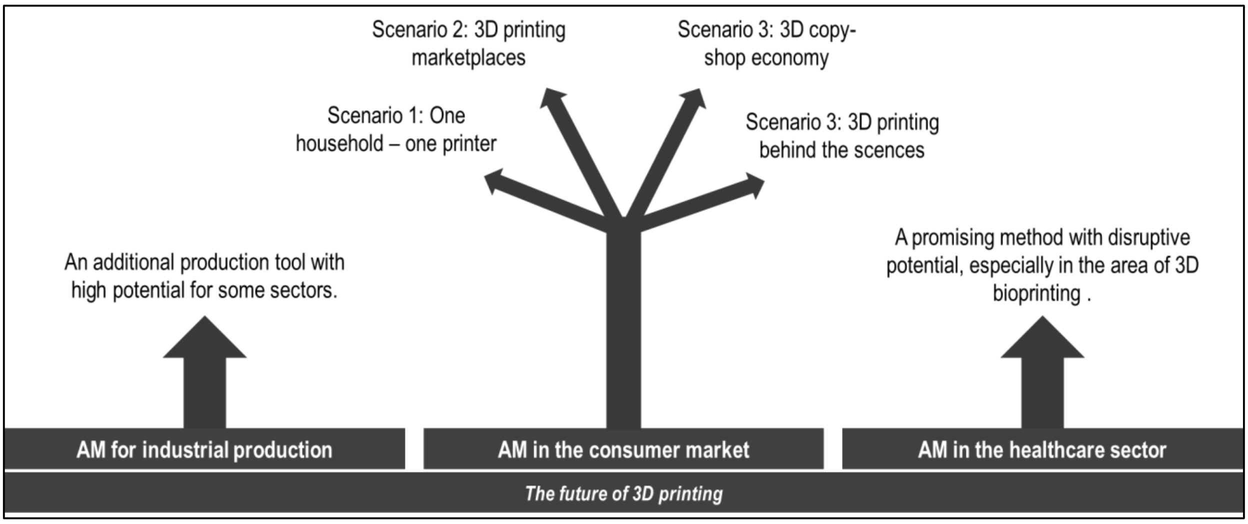

Figure 12: 3D printing: Quo vadis? Source: Own illustration.

5.2 Policy recommendations

As this report has demonstrated, additive manufacturing technology bears significant innovation potential in several areas. To generate first mover advantages and secure its role as a global leader in the area of engineering and high-tech manufacturing, Germany should encourage industry players and consumers alike to adapt this new technology, build up relevant expertise and develop a competitive edge. The following section presents specific policy recommendations for fostering 3D printing activities in Germany. The recommendations are clustered into three parts: (I) Recommendations to support the advancement of the technology as such and to facilitate its integration into manufacturing practices; (II) recommendations to deal with regulatory issues and framework conditions; and (III) recommendations to foster the adoption of 3D printing technology by end-consumers. Table 16 provides a summary of the recommendations, which are then explained in the upcoming sections.

Table 16: Overview of policy recommendations. Source: Own illustration.

Area	Recommendation
Part I: Unleashing the technology's full potential	I.I Public funding for fundamental and applied research
	I.II Establishment and support of interdisciplinary and trans-regional 3D printing clusters
Part II: Defining framework conditions for an emerging 3D printing market	II.I Establish an expert group to clarify open regulatory and legal questions
	II.II Investigation of new solutions in the area of intellectual property
	II.III Establishing mechanisms for consumer protection and quality assurance
	II.IV Developing new mechanisms for standardization and product approval
Part III: Enabling a thriving 3D printing landscape	III.I Enhancing general visibility of and accessibility to 3D printing technology
	III.II Integration of 3D printing in education agendas for schools and universities across disciplines
	III.III Establishing a 3D printing information platform for end-users
	III.IV Fostering entrepreneurship in the area of 3D printing

5.2.1 Part I: Unleashing the technology's full potential

I.I Public funding for fundamental and applied research

To unleash the full potential of AM printing technology and foster its integration in state-of-the-art manufacturing processes, additional research has to be conducted. Research topics thereby reach from fundamental research, for instance in the area of bioprinting and materials, to applied research, for instance for 3D printing applications and to investigate micro- and macroeconomic implications. The country comparison (see chapter 4.1) illustrated that certain countries, like the USA and China, already support advancements in 3D printing research with large public funds. Therefore, we propose the ongoing inclusion of AM-related topics into national research and innovation programs. Interviewee 7 furthermore emphasized the need for public funding especially in the area of 3D bioprinting since research in this area is still at an early stage making it difficult to generate private funding from industry partners. Interviewee 5 stressed that the first priority in supporting 3D printing in Germany should be funding of research and industry programs in order to solve existing technical challenges. Another proposal comes from interviewee 12 who suggested a research program that specifically focusses on additive manufacturing (instead of having more general manufacturing technology research programs) and that is tailored to small and medium-sized companies in that area. This suggestion aligns with recommendation III.IV.

I.II Establishment and support of interdisciplinary and trans-regional 3D printing clusters

Most experts, who were interviewed in the course of this study, agreed that the establishment of interdisciplinary and trans-regional 3D printing clusters could leverage current research and development activities. The full potential of 3D printing is only unleashed if expertise from different disciplines is merged into trans-disciplinary knowledge. Therefore, we propose the foundation of collaborative platforms that bring together experts from different disciplines (such as design, engineering, material sciences, medicine) and actively promote mutual knowledge exchange. Such collaboration platforms could follow first existing examples.

For instance, in 2014, the first open 3D Printing Cluster in Germany has been established by UnternehmerTUM (Technical University of Munich), the Strascheg Center for Entrepreneurship (Hochschule Munich) and EOS GmbH in Munich. The goal of the cluster is to create an interdisciplinary network of actors from all over Germany and to stimulate new innovative startups based on the industrial 3D printing technology (EOS, 2014c). Therefore, open networking evenings and information sessions take place on a regular basis in Munich.

Another international example for collaborative working spaces are the aforementioned four manufacturing innovation hubs that have been established in the USA to bring together businesses and the Departments of Defense, Energy, Commerce, NASA and the National Science Foundation. Such hubs enable businesses in the affected industries to inform themselves about AM and explore together with experts how they can adopt AM in their industry. This is a direct way to carry the benefits of AM into existing industries.

5.2.2 Part II: Defining framework conditions for an emerging 3D printing market

II.I Establish an expert group to clarify open regulatory and legal questions

As elaborated in chapter 4.4, the emergence of 3D printing technology and its broad dissemination creates a range of new issues in the regulatory and legal landscape. Answers to these questions require careful thought to balance competing policies, for instance in the area of intellectual property. Therefore, it is encouraged to establish an expert group existing of 3D printing experts, legal scholars and policy-makers to scope out the implications of 3D printing in the German and European regulatory system and to create a proposal for a 3D printing legal roadmap.

II.II Investigation of new solutions in the area of intellectual property

When defining the regulatory framework conditions for the German and European 3D printing market, particular focus should be put on possible new and innovative solutions in the area of intellectual property, such as micro-patents, new licensing mechanisms or encryption systems for file contents.

II.III Establishing mechanisms for consumer protection and quality assurance

To protect customers and minimize risks, mechanisms for quality assurance for 3D-printed products should be established. On platforms such as Shapeways, specialized shops[12] can sell their 3D design to users. It is advised that shops offering design files or printed models should comply with predefined quality standards and that commercially

[12] http://www.shapeways.com/shops

distributed products should be verified by an impartial third party. The model of this third party organization could be inspired by the German Stiftung Warentest with the goal to evaluate different aspects (e.g. functionality, durability & safety) and to offer a benchmark to the users, so that they can take educated decisions. Such standards can also include environmental norms for printers, emissions and feedstock material.

II.IV Developing new mechanisms for standardization and product approval

Even though 3D printing is already used regularly in automotive and aerospace industries for prototyping purposes, it is rarely used for manufacturing final parts of sold products. There is a huge potential of 3D printing in final manufacturing especially of customized and individualized products, which cannot be realized due to complex certification and approval processes for new parts. Costly approval and certification processes are an important barrier for realizing the added-value services especially in small batch productions and custom products. Changing the requirements from the focus on final parts to the focus on material properties (e.g. automatic approval for new individual parts, which are printed with standardized and certified material for which minimum wall thicknesses depending on tensile and pressure loads are defined), these processes could be accelerated. As this could unleash a huge potential of innovations and value creation, standardization institutions (e.g., International Standards Organizations or the Association of German Engineers) and regulatory authorities should address this topic and come up with new norms, standards and lean product approval processes.

5.2.3 Part III: Enabling a thriving 3D printing landscape

III.I Enhancing general visibility of and accessibility to 3D printing technology

To counteract the skepticism of AM and to increase technology acceptance, it is necessary to educate the broader public about the nature of AM and its potential. Therefore, several measures can be taken: First, policy makers can publicly show their trust in this new technology by including the topic in their policy agendas and supporting related events like fairs and exhibitions, such as Euromold 2014 in Frankfurt or the Maker Fair 2014 in Munich. Hosting and endorsing such events not only generates visibility for AM, but also might encourage entrepreneurship since the topic gains momentum and attracts potential innovators. Secondly, information campaigns through different channels and well-documented articles in mass media targeted to a lay audience can help to raise awareness for 3D printing. Thirdly, the establishment of public “maker spaces” in which consumers can explore 3D printing via experimental workshops can provide easy access to 3D printers and might foster small-scale innovation activities. In the USA, the innovation company TechShop is a highly successful provider of such “maker spaces”. In October 2013, it was announced that the BMW Group and the Entrepreneurship Centre at Technical University Munich (UnternehmerTUM) will open up the first TechShop in Munich in Spring 2015 (BMW Group, 2015).

III.II Integration of 3D printing in education agendas for schools and universities across disciplines

The adaptation of education is one of the most vital steps in facilitating the adoption of a new technology. Therefore, three recommendations with regard to the integration of 3D printing in education agendas for schools and universities are proposed:

First, 3D printing bears great potential as a toolkit for technology education in early childhood and adolescence. Especially desktop 3D printers with their ease of use and playful application possibilities (e.g. printing of toys and figurines) offer significant learning opportunities whilst maintaining the aesthetic aspects requested by children. By working with simple 3D printers, children may learn about the entire manufacturing process – from digital product design to object printing – in a fun, hands-on and understandable way. Therefore, 3D printing can significantly contribute to taking away children's fear of technology and foster early interest in technical topics. Currently, first schools in Bavaria[13] collaborate with institutions to offer 3D printing workshops to their students. The high demand for places in these workshops show that pupils are interested in the technology.

Second, since 3D printing is likely to affect different areas of production and industry, the topic should be integrated in university curriculums across various disciplines (interview 1; 2014; interview 4, 2014). This might not only include technical study programs like engineering or industrial design, but also non-tech study programs such as medicine or biology. Therefore, universities could establish AM Knowledge Centers that are open for students of all relevant study backgrounds, such as biology, industrial manufacturing and design. Here, special courses in innovation and product development can train students to take the new opportunities and concepts of AM into consideration. Such a measure would help to train "hybrid" designers and foster interdisciplinary discussions about the topic. Furthermore, in order to incentivize students to work with AM, universities, schools or public institutions can host competitions that aim on solving part design problems by understanding and applying the ways of designing and producing parts. These incipient actions should be leveraged by offering specific electives to students on all aspects of 3D printing (e.g., on intellectual property, computer-aided-design, material properties).

Third, even more specialized degrees in additive manufacturing, for instance as interdisciplinary Master of Science programs, could enrich the current graduate education landscape. One existing example is the Master's degree in Regenerative Medicine & Technology, a joint program that is offered by the Queensland University of Technology and the University of Wollongong in New South Wales, Australia, along with University Medical Center Utrecht (Netherlands) and the University of Würzburg (Germany) (Molitch-Hou, 2014b).

[13] http://www.gymnasium-trudering.de/fablab.html

III.III Establishing a 3D printing information platform for end-users

Whereas hubs and copy-shops can provide users with access to 3D printing technology, there often remains a high amount of insecurity with regard to intellectual property regulations on the user side. To support home 3D printing and small-scale innovation activities, the users should be well-informed about their rights to protect their own constructions and their limits to modify and use other people's creations. Therefore, it is advisable to develop prevailing and easy-to-use guidelines dedicated for 3D printing user innovation. Furthermore, users of 3D printers should be educated about possible environmental impacts, risks and the current lack of quality standards with regard to desktop 3D printing. One way of providing these services could include the development of a publicly funded web-based information platform.

III.IV Fostering entrepreneurship in the area of 3D printing

3D printing is an auspicious field for entrepreneurial activities, both directly in the additive manufacturing industry itself and in industries affected by these new manufacturing technologies. First, even though there are established players (e.g. Stratasys, 3DSystems, EOS, Makerbot) in the additive manufacturing industry, it is still a relatively young industry with promising very young newly started companies (e.g. AIO Robotics, Wamungo) and room for further startups to supplement the existing ecosystem within this heavily growing market. Second, 3D printing technologies can tremendously decrease entrance barriers for startups offering hardware-based products through the acceleration of developing processes and enabling competitive small batch production. Thus, additive manufacturing technologies could potentially enable the creation of new companies and lead to a sustainable economic growth and numerous new jobs. However, as there seems to be a lack of venture capital in Germany compared to other parts in the world (e.g. USA) possibly due to an overcautious and risk-averse mentality, public support in the form of venture capital and subsidies especially for the seed phase and early stages of startups could lead to a blossom of the German startup scene. Furthermore, innovation centers that bring together creative, ambitious and entrepreneurial students and young professionals of various complementary disciplines (e.g., mechanical engineering, computer science, electrical engineering, business administration) can foster the formation of successful founding teams.

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