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3D Printing – Risks and Opportunities

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1. Introduction

In the recent years parts of the manufacturing world have become very enthusiastic about 3D printing technology. Some people are even talking about a next industrial revolution. The news of a 3D printed pistol which was produced and fired by a student in the United States made the public aware of this innovative technology and the possibilities 3D printing offers.

In this context, the Greens/EFA Group assigned the Oeko-Institut to analyze the status and relevance of 3D printing more detailed. The main objectives of the study are:

- to evaluate the current state of play and future developments
- to identify potential risks and opportunities
- to analyze potential changes in manufacturing sectors and people's life
- to identify relevant EU legislation which might be affected by 3D printing.

In the present short-term project it was not possible to carry out intensive own research work and for example to interview relevant research institutions or businesses. Rather, the focus was on giving an overview and on the evaluation of available literature. The present report provides information and text from selected literature and own assessments of the Oeko-Institut.

The Oeko-Institut's report contains a short summary of the status-quo of 3D printing including technological aspects and current applications. It follows an evaluation of future developments which includes opportunities and potential benefits as well as risks and challenges. Thereby also legal and environmental aspects are taken into account.

In light of the enormous development and possibilities of 3D printing a large number of studies, reports and articles are already available. Many of them focus on the huge potential of (future) applications and on technical aspects. Others provide a good overview of the current status of 3D printing. Considering this study's limited possibilities the Oeko-Insititut's work focuses on aspects which so far have not been adequately taken into account.

2. Additive Manufacturing – Technology

The term *3D printing* is widely used and very popular with newspaper articles, other media and the general public. The term *Additive Manufacturing (AM)* seems to have more and more replaced 3D printing especially in industry and business and amongst researches, experts, professionals and other stakeholders. In this report both terms, 3D printing and additive manufacturing, are used and are exchangeable.

In order to explain additive manufacturing reports often refer to ASTM International's definition[1]. The Policy Brief "Global Review of Innovation Policy Studies", prepared on behalf of the European Commission, DG Enterprise and Industry also used this definition [European Commission 2013]:

"Additive Manufacturing – Defined by ASTM International (ASTM 2792-12): Additive Manufacturing (AM) is a process of joining materials to make objects from three dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. As a new tool in the entrepreneurial toolbox, additive manufacturing systems use computer-aided design models (CAD) and 3D scanning systems for production."

[1] ASTM International, formerly known as the American Society for Testing and Materials (ASTM), is a globally recognized leader in the development and delivery of international voluntary consensus standards. http://www.astm.org/ABOUT/overview.html

A good introduction to the AM process is given in [AtlanticCouncil 2011] and cited here:

“The AM process begins with a 3D model of the object, usually created by computer-aided design (CAD) software or a scan of an existing artifact. Specialized software slices this model into cross-sectional layers, creating a computer file that is sent to the AM machine. The AM machine then creates the object by forming each layer via the selective placement (or forming) of material. Think of an inkjet printer that goes back over and over the page, adding layers of material on top of each other until the original works are 3D objects.”

Under the heading of AM different technical processes are summarized. These processes can be differentiated by the material they use as a feedstock for AM and by the technique used for “adding” the layers. The most common types of materials for AM are metals, plastics and ceramics. Examples for techniques are for instance extrusion (plastics) or sintering/fusing with laser technique (e.g. metal and polymeric powder). The “Strategic Research Agenda” by the “AM Sub-Platform”, another fundamental study on AM [AM Platform 2013], and [AtlanticCouncil 2011] provide more details and a systematic overview of the different process techniques.

3. Status Quo – Applications

The following quotes, [Technopolis Group 2013] and [Technopolis Group 2013] give a good introduction to the status quo of the applications of AM:

“Engineers and designers have been using 3D printers for more than a decade, but mostly to make prototypes rapidly and cheaply. …the majority are used as functional models, prototypes, and casting patterns, or for presentation models. … As the technology is getting better more things are being printed as finished goods. … around 28% of the output of 3D printers is now final products rather than prototypes, and this is expected to rise to 50% by 2016 and 80% by 2020.” [Technopolis Group 2013]

“The compound annual growth rate (CAGR) of additive manufacturing was 29.4% in 2011... The CAGR for the industry’s 24-year history is 26.4%. The AM industry is expected to continue strong double-digit growth over the next several years. By 2015, Wohlers Associates believes that the sale of AM products and services will reach $3.7 billion worldwide, and by 2019, surpass the $6.5 billion mark.” [Wohlers Associates 2012]

In the following typical examples for applications of AM are presented. The focus of these applications is mainly on finished products taking pure research projects and prototypes only in exceptional cases into account.

Hearing aids

3D printing technology for manufacturing hearing aids was introduced more than 10 years ago. Using 3D printers for manufacturing hearing aids is common in this sector. “3D printing has shortened the hearing aid manufacturing process to three steps: scanning, modeling, and printing. …printers can print 65 hearing aid shells or 47 hearing aid molds within 60 to 90 minutes. The printing speed helps manufacturers scale and adjust demand to supply. In addition, the digital file helps modelers adjust and reuse ear impressions to correct for errors. In other words, 3D printers enable rapid prototyping and manufacturing.” [Forbes 2013]

Dentistry

3D printing is widely used in dental labs. With the help of oral scanning, CAD software and AM crowns, bridges, stone models and a range of orthodontic appliances can be produced [stratasys 2013].

Automobile components

BMW produces prototypes of metallic parts by using AM. Engine parts for motor sports racing cars also have been fabricated using direct metal laser sintering. Furthermore some luxury car manufacturers as Bentley and Rolls-Royce can produce some parts more economically by using AM instead of conventional manufacturing. Tesla, the producer of electric cars, also produces automobile components by using 3D printers. [Süddeutsche Zeitung 2013]

Aircraft components

“EADS has developed the technology to the extent that it can manipulate metals, nylon, and carbon-reinforced plastics at a molecular level, which allows it to be applied to high-stress, safety critical aviation uses. Compared to a traditional, machined part, those produced by AM are up to 65% lighter, but still as strong as those would be. The development of AM is an activity that spans the entire EADS group, with early applications in the production of fixtures and tooling for Airbus, and flying applications being implemented by Eurocopter and Astrium. EADS’ UK research facilities have the lead in the group’s AM activities.” [Technopolis Group 2013]

Airbus produced a door bracket for the A350-1000 in 2011 by using AM. For such components it takes the 200-Watt laser two hours to complete the print job. [Airbus 2011]

Boeing and other companies in the aerospace sector have also developed large internal AM research groups [Technology Strategy Board 2012].

The Boeing company has been utilizing SLS (Selective Laser Sintering) for flight hardware in regular production since 2002, for both military and commercial programs [Boeing 2011].

Tissue

For the first time the lower jaw of a patient was completely replaced by an artificial jaw which was 3D printed. Titanium powder was used for printing the implant. 1 mm of the implant exists of 33 printed layers. The titanium body is coated with bio-ceramics. [Spiegel 2012].

Parts of bones have been produced for some time by using 3D printing. Some of these man-made bones are even degradable and after some time will be replaced by the body’s own bone tissue. Also parts from faces or ears are more and more often produced by 3D printers. Therefore silicon is used as a material instead of titanium. [Spiegel 2012]

Future applications are 3D printed organs. However, research in this area is still far away from practical applications which would mean transplantation.

Scientists developed an artificial ear with the help of 3D printing. This is purposely different from the natural human ear. An antenna which is part of the artificial ear registers frequencies a human cannot hear. [Spiegel 2013a]

Weapons

The world’s first handgun made almost entirely by a 3D printer was printed and tested in 2013. 15 out of 16 pieces were printed by a 3D printer using ABS plastic as a material. The company which constructed the gun planned to publish the digital file for the gun online. The pictures of this 3D printed handgun which was only a prototype went around the world.

Sports

For the first time Nike produced a part, the plate, of a sport's shoe by using AM technique (Selective Laser Sintering technology, SLS)[2]. While the production of prototypes with the help of AM is common in shoe production this football shoe is the first finished product using AM.

Other applications

A huge range of different products can be purchased online. This includes jewelry, games, fashion (e.g. belts, wallets), lamps, furniture, articles for dining and other accessories, gadgets and design articles. This kind of products can be bought in specialized "print shops" or from websites specialized on 3D printed products as for example http://www.shapeways.com/.

Other applications exist also in the food sector. The University of Exeter developed a 3D printer for chocolate. After interests from retailers the scientists want to commercialize the 3D printing machine. The chocolate printer prints out chocolate layer by layer to create a 3D shape, without any molding tools. This gives the opportunity that own designs and chocolate articles can be created and printed out at local chocolate outlets. [3D Printing is the future 2012].

Another example in the food area is the production of creative food save molds. Customized molds made of food save silicone can be printed with a 3D printer. The "shoe burger" from the photo below was baked using the silicone mold from a 3D scanned shoe [Shapeways 2011]

Apart from the production of goods also the manufacturing of AM machines has become a business. Products range from comparably cheap 3D desktop printers for private households to complex high-tech machines for industrial use.

4. Opportunities, Risks and Challenges

4.1. Opportunities

Many articles and studies are quite optimistic with regard to the importance and use of additive manufacturing in future. "Mass market", "industrial revolution" and "disruptive technology" are common expressions in relation with the future development of additive manufacturing.

The following quotes [Atlantic Council 2011] show the enthusiasm with which 3D printing is often described.

"Assembly lines and supply chains can be reduced or eliminated for many products. The final product—or large pieces of a final product like a car—can be produced by AM in one process unlike conventional manufacturing in which hundreds or thousands of parts are assembled. And those parts are often shipped from dozens of factories from around the world—factories which may have in turn assembled their parts from parts supplied by other factories."

"Designs, not products, would move around the world as digital files to be printed anywhere by any printer that can meet the design parameters. The Internet first eliminated distance as a factor in moving information and now AM eliminates it for the material world. Just as a written document can be emailed as a PDF and printed in 2D, an "STL" design file can be sent instantly to the other side of the planet via the Internet and printed in 3D."

[2] http://www.nike.com/us/en_us/c/us-football/stories/2013/03/vapor-laser-talon, 7.11.2013

In the following some of the potential developments and opportunities are presented based on information from literature (e.g. [Big Innovation Centre 2012], [Atlantic Council 2011]).

Regarding future developments of additive manufacturing there are three different main categories for the application of 3D printing: 3D printing at private homes; bespoke AM at print shops and industrial manufacturing at factories.

3D printing at home: Comparable to desktop 2D printers and computers private households could own a 3D printer and print whatever and whenever they need something. 3D products would be tailor-made, individually designed and available at low costs. Digital files could be downloaded commercially or from open-source archives for free.

Print shops: Local retailers offer their services and use more sophisticated 3D printers of higher quality. Retail and production would be in one hand. Customers can send their own digital files for printing or choose from what the print shop offers. Another service could be making 3D scans of objects followed by the generation of a digital file and finally the printing of the product.

Factories: Final products can be produced in one single process with highly developed and specialized 3D printers. Supply chains, assembly lines and transports can be significantly reduced. New designs and functionalities are possible.

Apart from 3D products themselves the production of the raw materials for printing and AM machines present own business opportunities of high relevance. AM machines could range from mass market products for private households – today many 3D desktop printers are available for around 1,000 to 2,000 Euros and a cheap one for 200 US dollars [Spiegel 2013e] – to highly specialized AM machines for industrial use. Materials as feedstock for 3D printing will have to display very specific properties and could also become an own market.

Another area which is mentioned in context with AM is the production of spare parts. An option for manufactures would be to 3D print spare parts on demand instead of stock-piling them. Further on broken goods could be repaired by simply printing the specific component or a piece of the component or product which was damaged or maybe lost. A challenge could be that the 3D printed spare part could be made of a different material than the original and that the replacement needs to be fixed to the product especially if only a random piece of a component is considered.

Future developments and research offer great opportunities for AM. [Atlantic Council 2011] gives an outlook for potential future applications in medicine:

“In the past decade, significant advances have been made in using AM to “print” tissue scaffolds – biocompatible materials that, when implanted into the body and integrated with biological cells, assist in the regeneration of tissue. The geometric freedom offered by AM allows for the creation of scaffolds that are optimized to encourage cellular growth, while maintaining strength. In addition, recent advances have been made in direct printing of human tissue. These “bio-printers” could eventually permit the routine printing of replacement organs for transplant.”

Some more general developments and advantages of AM are explained in [Big Innovation Centre 2012] and cited here:

“*Customization and personalization* – 3D printers offer far greater scope for customizing products according to the needs of the customer. The shape, appearance and function of a product can be tweaked according to customer taste, or the needs of the environment it operates in. Products can also be bespoke designed from scratch where appropriate;

Reduced inventories – Instead of having to stockpile large numbers of products and trying to predict sales, 3D printing could allow manufacturers and retailers to operate with less stock, producing only what they need on demand. However, 3D printers would still require stockpiles of materials with which to operate;

Reduced capital costs – 3D printers should, in theory, reduce fixed capital costs for manufacturers, by reducing the need for large scale investment in factories and machinery. Of course, the costs of 3D printers themselves would still need to be factored in by manufacturers, but assembly lines and supply chains are likely to be vastly reduced;

Reduced transport costs – 3D printing should reduce transport costs, by removing the need for intermediate and finished goods to be shipped from one factory to another. While there will still be transport costs associated with materials, it is likely that these will be easier to source."

4.2. Sector specific developments

Predictions on future developments and potential benefits from AM often remain on a very general level without going into detail and without giving reasons for expected developments. A more detailed approach however is presented in [Big Innovation Centre 2012] for the UK in such a way that specific sectors and their potential for disruption from 3D printing are assessed. [AM Platform 2013] is another report which provides a much more detailed analysis for relevant sectors.

In the following the original assessment of [Big Innovation Centre 2012] is presented together with a comment by the Oeko-Institut for selected sectors. These comments take into account the assessment of [Big Innovation Centre 2012] and are based on the Oeko-Institut's general judgment without claiming to have knowledge of all developments in a respective sector. The comment is not targeted at the development of AM as such, but at the idea of being disruptive and of totally changing a sector.

- Food, drink and tobacco: "Unlikely to move wholly to 3D printing, although some components (including packaging) may be 3D printed within supply chains."

- Textiles, clothing and leather: "Likely to be heavily disrupted by 3D printing, with design, logistics and retail processes potentially transformed."

  Oeko-Institut: The share of cotton amounts to approx. 38 % of the total world market for textiles[3]. There is currently no technical development identifiable which would enable AM technology to make use of natural materials such as cotton or leather. Further on textiles and clothing are mass-products and their production is comparably cheap. Whether AM can compete with conventional production is completely open. AM could be more likely applicable for functional clothing or special designs made of plastics e.g. in the area of outdoor clothing or sports and clothing with integrated technical features.

- Wood and paper: "3D printing penetration will depend on ability to process different materials."

  Oeko-Institut: Solid wood cannot be produced, processed or in any way be used in AM. Any wood-based AM technology means the use of a "wooden" material such as something similar to a chipboard/particleboard, pellets or kind of plastics. Such a material which is already available for AM consists of a significant proportion of clue or binding agent and might be more

[3] http://zoibrina.wordpress.com/tag/baumwolle/; 31.10.2013

like plastic than wood [Spiegel 2013e]. Paper production is an integrated chemical process. Which role AM could play in this area is not evident. There is currently no technical development identifiable which would enable AM technology to produce or use a material such as paper. Also, what would be potential advantages of AM? On the other hand, the development of new materials using fibers from natural materials could become an option for AM. However, this could rather mean the development of new markets than replacing existing production processes.

- Printing and recording: “Printing and recording have already been hugely disrupted by shift to digital content; this is likely to be far more significant than 3D printing, as digital media dominate physical media.”
- Refined fuels: “Unlikely to be significantly affected by 3D printing.”
- Chemicals: “Some parts of the industry may be affected by shift to 3D printing, but complexity of chemical technologies likely to make 3D printing slow to disrupt.”

  Oeko-Institut: Chemicals are produced by chemical reactions under different conditions (e.g. gaseous, liquid, high or low pressure and temperature). This is totally different to AM, where chemical substances are added together mainly in order to build a new shape. AM applications as for example adding two components (like a kind of two-components glue) in order to react to a new synthetic material or application in the area of Nano materials can be imagined of. However, this would simply mean adding one more chemical process type to hundreds of other existing chemical processes.

- Pharmaceuticals: “Significant potential for on-demand manufacture of drugs in hospitals, although much will depend on technology.”

  Oeko-Institut: The main component of a drug is the active substance. The difficulties in the production of these substances were already described under the item “chemicals”. Or would “on-demand manufacturing” simply mean stock-piling hundreds of different pharmaceutical active substances and adding/mixing them together in order to form a pill? However what would be the potential benefit of this procedure?

- Rubbers and plastics: “High likelihood of disruption, especially for bespoke shaped plastics. Plastics are also likely to be the key material for 3D printing, which may be prompt innovation in development of plastics.“
- Oeko-Institut: A disruptive potential exists for the application of plastics as for example household items, parts of automobiles etc. The production of plastics (the material, not the application of the material) however is a mass production process which takes place in highly integrated chemical plants. There exists no apparent reason why or how this could change.
- Metals and building materials: “Potential for significant disruption from 3D printing. However, 3D printing may not provide the scale of production required for some industrial and construction processes.”

  Oeko-Institut: Although there is a research project on AM technology and concretely it is hard to imagine how AM could affect mass products as for example building bricks or concrete apart from perhaps special applications. The influence on metals will mainly depend on the technological development and on the ability to make different metals technical available for AM. This includes the question whether the same material specifications result for AM technology as for conventional production.

- Computers, electronics and electrical equipment: “Some potential for disruption from 3D printing, although issues of assembly and precision may limit uptake.”

- Oeko-Institut: The production of complex electronics uses a variety of different materials as for example precious metals and rare earths or semiconductor materials. Whether AM will ever be able to process these different materials and will result in the same functionality cannot be answered today. However, there exist some examples which indicate potential developments. In 2012 news about a 3D printed small unmanned aerial vehicle (UAV) was published [Watson 2012]. Two different AM techniques were used to first manufacture the wing structure of the UAV and afterwards to print the electronic circuits and active devices directly onto the wing structure. In [Sridhar 2010] the potentials of inkjet printing technology for electronics were described. Inkjet printing can be used to print passive circuit components like resistors, capacitors and inductors, as well as diodes, Organic Light Emitting Diodes (OLEDs) and circuit interconnections. This kind of electronics can be used for applications with simple electronics functions at low costs.

- Machinery: “3D printing is likely to play a major role in providing bespoke and on-demand machinery.”

- Cars and other vehicles: “3D printing is unlikely to remove assembly lines or end mass production, but may play a role in manufacture of components.”

- Ships and aerospace: “Large scale building projects make 3D printing unlikely, although may be involved in the supply chain.”

- Furniture: “3D printing should play a major role in re-shaping furniture markets, with designs and logistics heavily disrupted.”

  Oeko-Institut: Solid wood or natural leather cannot be processed by AM. Foam padding for seating furniture are mass products and at the present not very likely to be produced by AM. On the other hand AM offers the possibilities to create new designs together with new materials (see above “Wood and paper”). Whether these new designs and materials become established as a norm or become not more than a niche product could depend amongst others on the production costs.

- Other manufacturing: “Other manufacturing includes a range of low-tech, bespoke manufactures such as toys; these are likely to be one of the earliest markets for 3D printing.”

4.3. Risks and Challenges

When considering the potential benefits from additive manufacturing one also has to keep in mind a number of challenges associated with AM. [AtlanticCouncil 2011], [Digital Manufacturing Report 2012] and [Big Innovation Centre 2012] are examples for studies and articles which list risks and challenges for the development of AM.

Limitations in relation to speed: The 3D printing process is slower than conventional production processes. Examples of manufacturer's information for speeds of industrial 3D printers are e.g. 35 seconds per layer, 15 mm per hour or 40-50 mm per hour [voxeljet 2012]. Therefore manufacturing of large quantities of certain goods might be difficult and would require a considerable increase in speed of 3D printing respectively.

Materials: The choice of different raw materials as feedstock for 3D printers is still rather limited. There might be physical and technical limitations regarding the diversity of potential raw materials.

Further on the material's properties of 3D printed products in comparison with conventional manufactured products is a matter of research and differences in the material's properties might occur. At the present commercial 3D printed products usually consist of one single material. AM of complex products which are built of different types of materials in a single process step is according to Oeko-Institut's knowledge still a matter of research. Whether it will be ever technically possible to put ideas of e.g. 3D printed electronic goods such as smart phones into practice is not yet foreseeable. This would mean not simply adding together different types of materials but at the same time would require the materials to fulfill their functionality e.g. as part of a (electronic) component.

Another challenge is described in [Big Innovation Centre 2012] and cited here:

"*Real world proofing* – In theory, 3D printers may be able to replicate designs anywhere in the world, but there are a range of practical problems that may make the process difficult, especially for high precision operations. Changes in temperature and atmospheric conditions could conceivably affect the operation of 3D printers in different places, while there may also be a host of issues around lining up and configuring different processes correctly. While this problem should not be insurmountable, it may require specialized staff to operate 3D printers, and increase the complexity of the process."

Post-processing: Depending on the intended use of a product post-processing might become necessary. Post-processing cannot be done by the AM machine but is manually intensive process [Digital Manufacturing Report 2012]. In the case of a medium or high production volume this issue might become an important matter.

Environmental Aspects – See chapter 6.

Legal Aspects – See chapter 7.

Markets and Jobs – See chapter 5.

Articles and studies are often enthusiastic about future opportunities which AM might offer. A common feature is 3D printing at home. Sometimes the impression is given that almost everything could be 3D printed at home with tremendous possibilities regarding design and function. In addition and complementary to future opportunities the Oeko-Institut would like to amend some challenges and more critical aspects.

First of all the list of potential products is to some extent limited (see previous chapter). (Complex) electronic goods are fare away from being realized. Furniture and clothes are often made of solid wood, leather or cotton which at least in form of the original raw material cannot be used as a feedstock for AM. Further on 3D printing of furniture probably would require not just a small 3D desktop printer but a much bigger machine. Thus furniture and clothes would probably be restricted to certain materials and sizes only. Considering more complex products which consist not only of one single material but a variety of materials, it is questionable whether these could ever be printed with a simple 3D desktop printer if it will be at all possible and advisable for AM produced goods such as mobile phones, electric tools or watches.

Generally our products at home consist of a great variety of materials, therefore widespread 3D printing would require stock-piling of many different materials at home, which seems not very desirable. One can assume that the quality of a product probably is much better if the digital file is sent to a retailer and printed by a high-tech business 3D printer instead of being printed by a private 3D desktop printer.

Spoons, knifes, glasses, cups, plates and other articles of daily use are not very special and would afford some time to be printed by a 3D desktop printer. Would it really be more interesting and also cheaper to print ordinary household goods at home instead of simply ordering them from the internet?

Whether 3D desktop printers for private homes will be used only by design- and technically-oriented creative minds or become a mass product comparable to 2D desktop printers for paper cannot be foreseen at this time.

5. Research, Markets and Jobs

Research and Development

In respect with AM the United States, Israel, the United Kingdom, Germany and others and to some extent also China are considered as leading countries [Technology Strategy Board 2012], [Anderson 2013]. In the following a short overview on respective research and development (R&D) strategies, institutions and budgets are given without any claim to completeness.

In the United States a new public-private institute for additive manufacturing was announced in 2012 [The White House 2012]. This institute, the National Additive Manufacturing Innovation Institute (NAMII), a partnership which was selected through a competitive process, was awarded an initial $30 million in federal funding, matched by $40 million from the winning consortium. The consortium includes manufacturing firms, universities, community colleges, and non-profit organizations.

Within the UK, “£95.6 million has been invested in collaborative or university AM R&D projects and Technology Transfer activities … between 2007 and 2016. Of this, £80 million has been committed to research, with £15.6 million for technology transfer and business support. Industry has made a significant commitment to supporting AM research and technology transfer activities with £25 million invested, whilst public funding bodies contributed the majority of the balance with the Technology Strategy Board, the EU Framework Programmes (FP6 & FP7), and the European Regional Development Fund (ERDF) being the most significant supporters at approximately £13 million each.” [Technology Strategy Board 2012]

In Germany there are two research networks for AM, DMRC and the Fraunhofer Additive Manufacturing Alliance. The Direct Manufacturing Research Center (DMRC) is a research consortium which consists of national and international key players in research and industry [DMRC 2012]. The objective of the DMRC is to promote the development of additive manufacturing processes and systems and to make AM a standard production process. The overall DMRC budget is 11 million Euros till 2016 (5 years).

“The Fraunhofer Additive Manufacturing Alliance has earned a reputation as the largest inter-disciplinary European alliance of competence for high-speed processes enabling individual manufacturing of products made of metals, plastics, ceramics and other materials. Collaborating closely with national and international partners, the alliance develops new rapid strategies, concepts, technologies and processes to enhance the performance and competitiveness of small and medium-sized enterprises.”[4]

China has announced government plans to support AM and to develop a medium- and long-term strategy for AM. “…the newly formed China 3D Printing Technology Industry Alliance states that China’s 3D printing technology is “basically on the same level” as the United States, Israel, and

[4] http://www.fraunhofer.de/en/institutes-research-establishments/groups-alliances/additive-manufacturing-alliance.html ; 5.11.2013

other leading countries as a whole, but still lags far behind in materials and software development." China has also announced the establishment of a 3D printing industrial park which shall include a large rapid prototyping and manufacturing center. [Anderson 2013]

In addition to national institutions and networks there is also an international alliance, the so called Global Alliance of Rapid Prototyping Associations. "The Global Alliance of Rapid Prototyping Associations (GARPA), and its annual meeting, the Global Summit, were formed to encourage the sharing of information on additive manufacturing (AM, rapid prototyping and related subjects across international borders. As a part of this sharing, GARPA members from around the world participate in activities that include technical presentations at industry conferences, the publication of application case studies, business meetings, social events, and the formal and informal exchange of information."[5]

The "AM platform" is a virtual platform for additive manufacturing at the European level[6]. The platform aims at improving the collaboration on AM. The AM platform wants to contribute to a coherent strategy, a better understanding and further development, dissemination and exploitation of AM.

The Strategic Research Agenda [AM Platform 2013] provides an overview of European R&D projects in the field of AM. They list 21 projects taken from the European Union CORDIS website. The projects take place in particularly for development of AM technology and for applications in specific sectors. Another area is the standardization of AM.

Markets and Jobs

Visionary future scenarios about AM might describe a situation where nowadays economic structure would be totally changed. Production markets e.g. China as well as for example Germany's innovative medium-sized business structure will no longer exist. Instead, development countries no longer depend on imports but have their own additive manufacturing industry and produce whatever good is needed within the own country. Associated with such a development would be a general restructuring of the labor market. The number of typical production jobs would be significantly reduced. On the other hand AM would create other types of jobs such as designers, engineers, technicians, software programmers and other such occupations [Big Innovation Centre 2012].

Nobody can predict whether this kind of scenario will ever become true. Development and production of 3D printers, 3D scan technology, software development and design are indeed potential business areas which seem to be likely to profit from a further development of AM. However, there is still a long way from creating new jobs in the field of AM to disrupting job markets in other sectors. AM still needs to prove its practical suitability for a wider range of applications and in day to day use. Even if AM should influence (job) markets that does by far not mean that AM will ever have the power of changing (job) markets.

[AtlanticCouncil 2011] provides a more in-depth evaluation of changing manufacturing markets, possible fundamental shifts in the global economy and impacts on geopolitics.

[5] http://www.garpa.org/main/ ; 6.11.2013
[6] http://www.rm-platform.com/index.php?option=com_content&task=view&id=17&Itemid=31; 7.11.2013

6. Environmental Aspects

It is very common in articles and reports on AM to claim that environmental benefits will result from 3D printing and companies will be able to reduce the carbon footprint of their products. Arguments often are reduced transports and supply chain activities. However, apart from these theses no sufficient explanations are given and scientific analyses are missing.

Life Cycle Analysis

In 2013 a Life Cycle Analysis (LCA) on AM was actually published using three concrete 3D printed products as examples [LCA 2013]. This LCA gives a more differentiated picture of the environmental aspects related with AM. From Oeko-Institut's point of view the LCA reveals two important factors which are crucial for the cumulative energy demand (CED[7]) of 3D printed products: the choice of the material which is used for manufacturing a given product and the amount of a material which is practically used for 3D printing compared to conventional manufacturing.

One of the examples of the LCA is a block, a toy which is normally made of hard wood. The CED of the 3D printed plastic block was always higher than the one made of massive wood (100 % fill) independent of the type of plastic used for 3D printing (two different plastics were used) and independent of the amount of plastic (massive block with 100 % fill to a hollow block 0% fill). These results show that AM requires certain materials as a feedstock which might replace a raw material with a potentially higher or lower CED.

The comparison of a theoretically conventional manufactured plastic block (100 % fill) with the 3D printed plastic block shows that the 3D printed block consumes less energy mainly because it uses less material (less than 25 % fill).

At this stage no universally valid conclusions are possible. Depending on weight savings which might be achieved for an individual product a reduction of the energy demand for 3D printed products is possible. Further on these products will be more resource efficient. On the other hand renewable resources as for example wood cannot be used for 3D printing. Therefore a shift to plastics or metals might occur for certain 3D printed products resulting in potentially higher energy demands.

A potential risk related to 3D printing at home might be that more products could be produced because they can simply be printed at home, and that products could more often be replaced because its design is no longer liked.

Wastes

Waste management is also an area which might be affected by 3D printing. Especially for complex 3D printed products made of different materials recycling might become difficult. Therefore a pre-requisition for the recycling of 3D printed products would be a clear labeling of the materials used for the production. On the other hand less production waste will theoretically occur because 3D printing uses only the amount of material which is needed to form a given product. Any surplus material (e.g. metal powder) in principle can be reused for the next product. This aspect also supports the resource efficiency and a lower carbon footprint of 3D printed products. However one has to keep in mind that in practice for example faulty batches might be produced and in case of a variety of different raw materials the materials need to be separated again afterwards. Thus day to

[7] In this context CED can be considered instead of the global warming potential (GWP) and delivers similar results as the carbon footprint of the product.

day practice still needs to prove theory. Potential wastes from AM could result from filling and supporting material which is used to fill unused spaces during the production process and which is removed after the finishing of the product. The reduction of hazardous wastes is another advantage of AM. AM technique does not directly use relevant amounts of hazardous chemicals [AM Platform 2013]. Hazardous wastes, however, can occur from conventional production processes (for example cooling agents and lubricants).

General aspects

Generally the total life cycle of a product is relevant for its environmental performance. Considering only reduced transports and supply chain activities is misleading. Even more as especially transport normally has only a small share of the total environmental impact of a product. Manufacturing of the raw material, however, often has a significant share of the environmental impact. Therefore it is very important whether a product is made of metal, plastics or a natural material. Shifting from natural materials as for example wood to plastics might have a much higher impact or energy demand than the way how a material is processed (i.e. 3D printing or conventional production). Depending on the type of product the use phase can be the determining factor. This applies especially for automobiles or airplanes. 3D printed parts potentially use significantly less material and thus are lighter than a conventional manufactured part. The reduced weight results in less fuel consumption (use phase) which in turn is more relevant than the manufacturing phase of the car or plane.

7. Legal Aspects

Additive manufacturing potentially has implications on existing laws and regulations or might require adaption of legislation or even new legislation for AM related aspects. In the following some relevant areas are explained.

Intellectual property rights

The development of 3D printing is closely linked to the idea of open-source. However, if 3D printing is to become a new worldwide technology and Additive Manufacturing products and services will represent a relevant share of our economy, then intellectual property rights will play an important role. From a business point of view designs, ideas and processes need to be protected otherwise the business approach risks to fail. Costumers on the other hand are much in favor of copying products or digital files for free. Authors often compare potential implications or developments of Additive Manufacturing with the situation of the copyright of music and movies in connection with the internet.

Another aspect of intellectual property rights of AM represents its influence on the competitiveness. Only a few companies or institutions might own relevant intellectual property rights of AM technology and as a result prevent competition and the development of new applications [AM Platform 2013].

[Bradshaw 2010] provides a more detailed analysis of the existing UK legislation in relation to intellectual property rights and AM. The focus of this article is on small firms and private individuals. An outcome of the study is that within the UK at least AM items made for personal use and not for gain and printed on private 3D desktop printers are exempt from the vast majority of intellectual property constraints. According to [Bradshaw 2010] there are a number of registered and unregistered rights which need to be considered with respect to intellectual property rights.

The *copyright* is an unregistered right that protects mainly artistic and creative works. A *patent* is a registered right that protects novel and innovative products such as mechanisms or chemical compounds. Registered *trademarks* serve to inform consumers of the origin of goods. Further on *design protection* exists in both registered and unregistered forms and protects the distinctive shape and appearance of items (in particular those that are mass-produced). [Bradshaw 2010]. A similar work was published by Weinberg in the United States [Weinberg 2010], [Weinberg 2013].

Legal responsibilities

Different processes and persons or companies are involved in the production of 3D printed objects, e.g. companies which develop and manufacture 3D printers; companies or individuals producing digital files of 3D objects (open source files); and companies, “print shops” or private persons doing the actual printing of an object. The 3D printed product might become defective or maybe more relevant or significant the products might cause accidents. Therefore questions regarding the liability of 3D printed products need to be considered. Could or should there be a legal guarantee for 3D printed products? Who is legally responsible in case of an accident: The company which provided the 3D printer, the developer of the digital file or the person who did the actual printing? A clear legal framework needs to be developed for these purposes.

Regulation

A challenge will be to provide sufficient space for innovations and further development of 3D printing and at the same time to provide a legislative environment which minimizes potential risks of 3D printing. In this respect regulations will be needed especially for controlling 3D printed objects for potential criminal use as for example guns, keys or the manipulation of ATMs. Another area which might need to be looked into are safety of employees and production processes (e.g. use of lasers, high temperature applications). This applies for the use of 3D desktop printers at home too.

The German federal police for example are dealing with this problem. The US tries to develop draft laws to prevent 3D printing of weapons and manufacturer of 3D printer develop software to prevent the printing of weapons. [Zeit online 2013]

In the US the “Undetectable Firearms Act” was about to expire on 9 December 2013. This would have allowed the production of firearms which cannot be detected with metal detectors. Therefor the democrat Senator Schumer and others tried to develop a new law that should replace the old one. The House of Representatives now voted for the extension of the law for another ten years. The approval by the Senate is still outstanding. However, the law will not prohibit 3D printed weapons in general but the production of undetectable weapons only. [Bold Economy 2013], [Handelsblatt 2013]

In Philadelphia the City Council voted to ban 3D printing of firearms. Lawmakers in California and Washington DC vowed to push for similar bans. [NBC 2013]

Markings and Labels

Mandatory and voluntary requirements for product standards could have a potentially high impact on 3D printed objects and the other way round Additive Manufacturing could influence the product quality respectively. An example could be the CE marking, which is the manufacturer’s declaration that the product meets the requirements of the applicable EC directives (e.g. Toy Safety Directive). Simply because of the diversity and the high number of potential products it is hard to imagine how an appropriate controlling could be carried out. Further on a fundamental question is what would be eligible for labeling (e.g. the “Blue Angel” or the EU Flower eco-label) the actual product which might be printed at home or the digital file of a 3D object?

Standardization

Common standards need to be developed in order to ensure that companies involved in 3D printing as well as consumers and users can effectively use the required software and hardware for 3D printing. Standardization is required for example to make sure that a printed product is identical independent from the 3D printer used for printing. Therefore standards are needed for example for technical parts of the 3D printers; the specifications of the materials used as a feedstock for AM or the digital file of a 3D object.

As a response to the need for standardization in the field of AM a number of initiatives on national and international levels were launched. Amongst others ASTM[8] and ISO[9] have established technical committees for the development of AM standards. CEN/STAIR is leading the standardization process at the European level[10]. [AM Platform 2013] provides an overview of the different activities. China's strategy for AM (see chapter 5) also includes promoting the formulation of codes and standards [Anderson 2013].

8. Outlook

Recommendations regarding the future development of AM exist in great variety and number. The Strategic Research Agenda [AM Platform 2013] provides a good summary of concrete recommendations for specific sectors and areas and for AM as a whole. Its overview on the need for research and development takes into account technical aspects but also areas like education and training or for example standardization.

However, there are some areas which have not so far been adequately looked at and analyzed. In the following these areas, respective recommendations and need for research, are presented.

Environmental Aspects

AM technology is also mentioned in context with sustainable production. The current knowledge on AM indicates potential environmental benefits in some areas compared to conventional production. However, from Oeko-Institut's analysis in chapter 6 it is obvious that up to now only single aspects have been considered. A comprehensive approach (incl. for example the total life cycle of products and applications and developments in different areas) and scientific analyses are missing. Such a scientific environmental assessment of AM would also be helpful for and include the identification of potential improvements of the environmental performance of AM production processes and products respectively.

Legal Aspects

Many reports and studies on AM are well aware of potential legal implications of AM and its potential developments. While critical aspects are often described it seems from the present study's findings that for some areas there is a lack of in-depth analysis.

Standardization is the field which is fairly covered. Concrete AM standardization initiatives on national and international levels are ongoing. Regarding intellectual property rights some basic work was done in the US and the UK. However, nothing comparable seems to exist on intellectual property rights at the overall European level.

8 http://www.astm.org/COMMITTEE/F42.htm; 7.11.2013

9 http://www.iso.org/iso/home/standards_development/list_of_iso_technical_committees/iso_technical_committee.htm?commid=629086; 7.11.2013

10 http://www.cencenelec.eu/news/events/Pages/EV-2013-07.aspx; 7.11.2013

Other areas described in chapter 7 show up more or less weaknesses and problems. Legal responsibilities in case of accidents; regulations in context with potential criminal use of AM applications and in context with safety aspects; and markings and labels as for example the EU Flower eco-label are areas with need for action. While for example in the area of potential crimes there exists a growing sense of the risks and some initiatives are ongoing [Zeit online 2013], it seems – at least from the literature evaluated for this study – that a structured and coordinated approach at the European or better global level is missing. A need for action applies especially with regard to the ongoing further development of AM and more and more practical applications. Intellectual property rights could then move on one of the top positions of the agenda.

Research and Development

From the different institutions and R&D initiatives (see chapter 5) it is obvious that research at the European level is on the way. The present study of the Oeko-Institut does not allow for an assessment of current research activities. Are R&D activities sufficient or do they need to be increased? However, a potential improvement could be a better coordination of and a better linkage between institutions and projects. A similar comment was made in [AM Platform 2013].

Apart from that AM has also a great potential to influence and change other areas such as the labor market – jobs for designers, engineers, technicians or software programmers might be created while typical production jobs could be lost – or the economic development of certain sectors. However, such developments cannot be foreseen at the present point in time and therefore would be nothing but speculative.

9. Literature

3D Printing is the future 2012	3D Printing is the future: "Chocolate printer to go on sale after Easter". 2012. http://www.3dfuture.com.au/2012/04/chocolate-printer-to-go-on-sale-after-easter/ (accessed: September 18, 2013).
Airbus 2011	Airbus: "Bringing new dimensions to Airbus production through Additive Layer Manufacturing". 2011. http://www.airbus.com/newsevents/news-events-single/detail/bringing-new-dimensions-to-airbus-production-through-additive-layer-manufacturing/ (accessed: September 11, 2013).
AM Platform 2013	Additive Manufacturing: Strategic Research Agenda (SRA), AM Platform, 2013 http://www.rm-platform.com/linkdoc/AM%20SRA%20Consultation%20Document.pdf
Anderson 2013	Anderson, E.: "Additive Manufacturing in China: Threats Opportunities and Developments". Part of "Study of Innovation and Technology in China". Institute for Global Conflict and Cooperation, University of California. SITC Bulletin Analysis. 2013.
Atlantic Council 2011	Campbell, T., C. Williams, O. Ivanova and B. Garrett: "Could 3D Printing Change the World? Technologies, Potential and Implications of Additive Manufacturing", a Strategic Foresight Report from the Atlantic Council. Washington: 2011.
Big Innovation Centre 2012	Big Innovation Centre 2012: Sisson, A.; Thompson, S.: Three Dimensional Policy: Why Britain needs a policy framework for 3D printing. Study of Big Innovation Centre. London: 2012.
Boeing 2011	"Additive Manufacturing in Aerospace, Examples and Research Outlook"; Brett Lyons, The Boeing Company, National Academy of Engineering, Frontiers of Engineering 2011, Additive Manufacturing; 19 September 2011 http://www.naefrontiers.org/File.aspx?id=31590
Bold Economy 2013	http://www.boldeconomy.com/aktuell-3d-waffengesetz; 5 December 2013
Bradshaw 2010	Bradshaw, S.; Bowyer, A.; Haufe, P.: "The Intellectual Property Implications of low-cost 3D Printing". Scripted. Volume 7, issue 1. 2010.
Digital Manufacturing Report 2012	Digital Manufacturing Report: "Additive Manufacturing's Dirty Secrets Exposed". Tabor Communications, Inc. San Diego: 2012.
DMRC 2012	"Forschungsförderung Additive Manufacturing im Direct Manufacturing Research Center DMRC" Dr.-Ing. Eric Klemp, Direct Manufacturing Research Center (DMRC) at University Paderborn, September13, 2012; http://www.rp-netzwerk.de/images/stories/pdf/rapid_6/Universitaet_Paderborn_DMRC_Vortrag2_RPForum2012.pdf

European Commission 2013	European Commission: New Themes in Innovation Policy – New Requirements for Innovation Policy. INNO-Grips policy brief, prepared by IW Consult Cologne. Bonn/Cologne: 2013.
Forbes 2013	Sharma, R.:"The 3D Printing Revolution You Have Not Heard About". Forbes. http://www.forbes.com/sites/rakeshsharma/2013/07/08/the-3d-printing-revolution-you-have-not-heard-about/ (accessed October 2013).
Handelsblatt 2013	Handelsblatt online, „USA verlängern Verbot von Plastikwaffen", 4.12.2013 http://www.handelsblatt.com/politik/international/pistolen-aus-dem-3d-drucker-usa-verlaengern-verbot-von-plastikwaffen/9166030.html; 5.12.2013
LCA 2013	Megan Kreiger and Joshua M. Pearce: Environmental Life Cycle Analysis of Distributed Three-Dimensional Printing and Conventional Manufacturing of Polymer Products; Michigan Technological University, Houghton, Michigan, United States; 23 September 2013 http://pubs.acs.org/doi/abs/10.1021/sc400093k
NBC 2013	NBC 10 Philadelphia; „Philadelphia Votes to Ban 3-D Printed Guns", 22 November 2013 http://www.nbcphiladelphia.com/news/local/Philadelphia-Votes-to-Ban-3D-Printed-Guns-232941351.html; 5 December 2013
Shapeways 2011	Shapeways: „Ready to Eat: 3D Printed Shoe Burger". The Shapeways Blog: 3D Printing News & Innovation. 2011. http://www.shapeways.com/blog/archives/977-ready-to-eat-3d-printed-shoe-burger.html (accessed: September 18, 2013).
Spiegel 2012	Dambeck, H.: "Knochenersatz: Frau erhält neuen Unterkiefer aus 3D-Drucker". Spiegel online. Hamburg: 2012. http://www.spiegel.de/wissenschaft/medizin/knochenersatz-frau-erhaelt-neuen-unterkiefer-aus-3d-drucker-a-813885.html (accessed: September 23, 2013).
Spiegel 2013e	Erste Maker Faire in Deutschland Basteln für Nerds - SPIEGEL ONLINE; http://www.spiegel.de/netzwelt/gadgets/erste-maker-faire-in-deutschland-basteln-fuer-nerds-a-914805.html (accessed November 11, 2013)
Sridhar 2010	Sridhar A, Attanasio D, Nannini A (2010). Trends and Expertise Exchange within Rapid Manufacturing in Europe. RTejournal - Forum für Rapid Technologie, Vol. 7. (urn:nbn:de:0009-2-23777); November 7, 2013
stratasys 2013	Stratasys: "Digital Dentistry 3D printing makes digital dentistry happen": http://www.stratasys.com/industries/dental; (accessed: October 2013)
Süddeutsche Zeitung 2013	Crocoll, S.; Brühl, J.: „3-D-Drucker: Wie die Industrie gehackt wird". Süddeutsche Zeitung Digitale Medien GmbH/ Süddeutsche Zeitung GmbH. Munich: 2013. http://www.sueddeutsche.de/wirtschaft/-d-drucker-wie-die-industrie-gehackt-wird-1.1583784 (accessed: September 13, 2013).
Technology Strategy Board	Quarshie, Dr. R.; MacLachlan, S., Reeves, Dr. P.; Whittaker, Dr. D.; Blake, R.: "Shaping Our National Competency in Additive

2012	Manufacturing". A report from the Technology Strategy Board's Additive Manufacturing Special Interest Group. Swindon: 2012
Technopolis Group 2013	Peter, Dr. V.; Izsak, K.; Bruno, N.; Castel, J.; Roman, L.: Developing an evaluation and progress methodology to underpin the intervention logic of the Action Plan to Boost Demand for European innovations. Final report of Technopolis Group on behalf of European Commission and DG Enterprise and Industry. Brussels: 2013
The White House 2012	Office of the Press Secretary: "We Can't Wait: Obama Administration Announces New Public-Private Partnership to Support ". The White House. Washington: 2012. http://www.whitehouse.gov/the-press-office/2012/08/16/we-can-t-wait-obama-administration-announces-new-public-private-partners (accessed: September 10, 2013).
voxeljet 2012	Christian Träger, voxeljet technology GmbH: „Industrieller 3D-Druck - vielfältige Möglichkeiten in Größe und Geschwindigkeit"; Presentation at 6 th Rapid Prototyping Forum, Merseburg; 13 September 2013 http://www.rp-netzwerk.de/images/stories/pdf/rapid_6/voxeljet_vortrag_rpforum2012.pdf
Watson 2012	Watson, S., March 2012. 3D PRINTING IS MERGED WITH PRINTED ELECTRONICS, http://www.optomec.com/site/latest_news/news95; (accessed: November 8, 2013).
Weinberg 2010	Weinberg, M.: "It will be awesome, if they don't screw it up: 3D Printing, Intellectual Property, and the Fight over the Next Generation Disruptive Technology". Public Knowledge. 2010. From Public knowledge: http://publicknowledge.org/it-will-be-awesome-if-they-dont-screw-it-up (accessed: September 12, 2013).
Wohlers Associates 2012	Wohler Associates: "Wohlers Associates Publishes 2012 Report on Additive Manufacturing and 3D Printing: Industry Study Shows Annual Growth of Nearly 30%". Press Release. Fort Collins: 2012. http://wohlersassociates.com/press56.htm (accessed: September 13, 2013).
Zeit online 2013	http://www.zeit.de/digital/internet/2013-07/waffen-3d-drucker-filter-software/seite-1 (accessed: November 11, 2013)