WORKING PAPER

Additive manufacturing: A layered revolution

Impact of game-changing technologies in European manufacturing

Future of manufacturing in Europe

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Related reports: This case study is one of the five case studies conducted in the framework of the project Future of Manufacturing in Europe: Joost van Barneveld and Tommy Jansson (Additive manufacturing: Layered revolution); Carlos Hinojosa and Xavier Potau (Advanced industrial robotics: Taking human-robot collaboration to the next level); Markus Lindström and Thomas Heimer (Electric vehicles: Shifting gear or changing direction?); Gaëtan Coatanroch and Andreas Ligtvoet (Industrial biotechnology: Reinvention of supply chains requires skills to deal with uncertainty and change); Chiel Scholten (Industrial internet of things: Digitisation, value network and changes in work).

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Executive summary

This report describes how Additive manufacturing (AM) changes the way products are made and what this means for work. The introduction of AM in manufacturing industries will impact **value chains**, **business models** and specific activities such as **product design** and **prototyping**. These changes require employees that are ready to work with the technology itself and that are open to changes in production processes.

Though AM can be positioned as a game changing or breakthrough technology, AM in itself is not new and the **increasing maturity of AM** technologies is a steady and slow process. Recent (rapid) adoption of the technology is driven by expiry of patents, miniaturisation of equipment and increase computing. In essence, AM is the revolution of *turning data into things*[1], which enables:

- Mass-customisation;
- Previously unavailable geometry;
- Complexity for free;
- Material efficiency gains; and
- Supply-chain simplification.

Additive manufacturing is, in one version or another, available for **any type of material**: metals, ceramics, plastics and biomaterials. Most probably, AM will be deployed on a 'material per material-basis' because the technologies for different materials vary so from one another (in terms of maturity, flexibility, costs, safety risks, etc.).

AM is applied mostly in **manufacturing industries** where the following parameters influence decisions about technologies and production processes:

- High added value of customisation;
- Small batch size;
- Design complexity;
- Importance of low weight; and
- Drastic assembly reduction.

Therefore, AM is applied most prominently in the **aerospace**, **automotive** and **medical industries**. In addition, there are broader, horizontal applications of AM as a technology to produce **components** for equipment manufacturing, **prototypes** and **spare parts**. Especially for these applications, the technological developments and the cost effectiveness and price of AM (mostly for metal) are important **drivers**. Other drivers (or enablers) are the extent to which AM can deliver on parameters such as reducing weight and simplifying assembly lines. **Barriers** are mostly seen in technological immaturity (depending on the material used), standardisation and interoperability issues, a lack of certification and to some extent IP concerns. Nonetheless, there is little doubt that AM is here to stay in one form or another, as several manufacturing industries are investing heavily in new production technologies (e.g. 3D printers), materials and applications of AM.

Because AM implies that design can more easily be translated into production, without the need for all too detailed manufacturing process knowledge, AM shifts the focus towards **design and creativity**. By means of digitisation and robotisation (AM is in fact a very specific robot), AM further reduces direct human involvement in the manufacturing process. The role of **process operators/supervisors** will continue to be important, while there will be less need for **assembly line workers**.

Because AM equipment is no longer specific to a single kind of product (such as injection moulding) but only to a material, AM equipment can be used more **flexibly**. This flexibility can be leveraged by companies and individual seeking to use 'idle time' for cheap production slots or even 'general

[1] A phrase often used by MIT's Neil Gershenfeld

purpose factories'. Examples in this report demonstrate that this enables new business models such as 'bridge manufacturing'.

These changes in the production process imply that, increasingly, the tasks and occupations of managers, designers, process operators and engineers **overlap**. At least, it becomes more important to efficiently and dynamically **collaborate**. This is facilitated by individuals and teams that are **multi-disciplinary**. The shift from process responsibility to product responsibility illustrates these changes. Indeed, team work is becoming more important as the chances of a single employee mastering all required skills at the same time are slim.

Because AM also increases the possibilities to use IT and **automate** processes, the importance of **IT and data literacy** increases. Whether AM reduces or increases the number of jobs in Europe or the world at large is a topic of heated debate. Assembly tasks can be greatly reduced with AM's ability to deliver more complex designs in one run. The prospect of multi-material printing only amplifies this development. On the other hand, the current state of AM requires manual post processing for most parts, which sometimes requires new processes. Moreover, AM does not substitute mass production (that still accounts for most of the companies and jobs). For instance, this report describes that the hearing aid production industry has seen **re-shoring**, partly because of the importance of small batch production and customisation. Re-shoring is less obvious for manufacturing of highly standardised or bulk products such as electronic equipment.

Flexible production systems enabled by AM could lead to more **flexible work schedules**, depending on client needs and worker availability. However, this effect can be small because economic considerations such as maximising asset usage also apply to AM. Therefore, 24/7 production shifts would still be the most logical choice.

A **consumer revolution** in the sense of 'click to materialise' is not expected due to the nature of products desired at homes (usually mass-manufactured plastics) and the relative complexity of home 3D printing. Local production hubs and maker spaces, where local specialists and inventors convene, are a more realistic conception of the democratisation of production. One could still consider this to be revolution in manufacturing.

Because AM production environments are digitalised and robotised, they are expected to be **cleaner** and (mechanically) **safer**. However, little is known about other safety aspects, such as chemical and electrical safety. Several experts raise concerns over nano-particles that may be emitted by AM, depending on the materials and equipment used.

Education institutions and **policy makers** respond to AM in the broader context of **Industry 4.0.** As such, research, innovation and experiments in AM are closely linked to the use of Advanced industrial robotics (AIR) and the Industrial internet of things (IIoT). AM and Industry 4.0 in general have triggered increased collaboration between industry and educational institutions. Here, the emphasis on technical skills further increases (materials, engineering, IT, etc.), while design, creative and communication skills are also invested in (see the concept of 21st century skills). This applies to formal education, at all levels, but also to training of employees. Because of the various established and emerging applications of AM, AIR and IIoT, in a wide range of industries, the need for flexibility is stressed. This also means flexibility in terms of combining and expanding skills (see the concept of lifelong learning). One of the options is to shorten formal education and allocate more budget (public and private) to training of employees, employers and self-employed experts.

To conclude, Additive manufacturing is a **revolutionary technology** that will no doubt have a large impact on the European manufacturing industry. The picture is clearer with respect to tasks, skills needs and working conditions, than regarding the number of jobs across the AM value chain. Current occupations will cease to exist and new ones will be created. AM certainly makes manufacturing more flexible and enables new business models. It also requires a more digitally literate, flexible and interdisciplinary work force, just like Advanced industrial robotics and the Industrial internet of things do. Education institutions, together with companies, are right to adapt education and training, to further strengthen a flexible workforce.

Introduction

Purpose and context of the study

This report about **Additive manufacturing** (and the underlying technologies) is one of the deliverables of a study that explores the impact of five technologies on manufacturing industries in Europe. Interactions with service industries are touched upon. The time horizon is 2017-2025.

The main purpose of the study is to better understand, and allow stakeholders to **anticipate and address** the impact of new technologies on production processes and work. As such, the three components of the study are:

1. The level of maturity and the scope of applicability of the **technologies**, in terms of specific sub-industries and geographic areas across Europe;
2. The (potential) qualitative impact on the **production process** including the impact on value chains, business models, productivity and output/products; and
3. The (potential) qualitative impact on **work**, in terms of employment (e.g. occupations that are emerging or disappearing), tasks (e.g. changes in physical, social and intellectual tasks), skill types and skill levels, education/training needs, working conditions.

The study also explores the interactions between companies, industry associations, trade unions, education/training institutions, governments and other stakeholders, during the changes that are affecting manufacturing industries. In short: actions by social partners. The detailed research questions are listed in Appendix A.

To set the scene for this study:

- The study takes **technology** as the point of departure…
- …but acknowledges that technological **trajectories** are influenced by established actors (with vested interests), new entrants (e.g. disruptors), path dependencies, social partners, policy and regulation, and much broader economic, social and environmental developments.
- The context of the study includes **cross-cutting technologies** such as ICT…
- …and **economic, societal and policy debates** about global value chains, industry 4.0 (and overlapping concepts such as factories of the future, smart industry and advanced manufacturing), re-shoring, 21st century skills, lifelong learning, flexible labour markets, resource scarcity, etc.

Note that the qualitative approach implies that the study **complements quantitative studies** about the impact of technologies (and automation and robotisation) on the number of jobs in specific industries and occupations. As such, this study is more about exploring the relevant mechanisms, uncertainties and important details such as changes in tasks and working conditions. This is done by means of looking into specific technologies and their application in specific industries.

The study about game changing technologies in manufacturing industries is part of the programme **The future of manufacturing in Europe** (FOME) financed by the European Parliament, under responsibility of DG GROW. The main theme of this programme is the revival of manufacturing in Europe. The economic and social importance of this revival are explained the 2014 European Commission Communication ‘For a European Industrial Renaissance’ (COM/2014/014/final). Under the umbrella of this policy agenda, specific policy actions coordinated by the European Commission address Key Enabling Technologies (such as ICT and biotechnology), research and innovation (e.g. the Leadership in Enabling and Industrial Technologies programme in Horizon 2020), the European internal market for products and services (e.g. standard setting for digital services), re-industrialisation of regions (e.g. using the Smart Specialisation Platform and the European Structural and Investment Funds), support for entrepreneurs and SMEs (e.g. the Enterprise Europe Network), skills development (e.g. the Erasmus+ programme) and collaboration between education institutions, research organisations and companies (e.g. the Knowledge and Innovation Communities within the European Institute of Innovation and Technology).

The FOME programme is executed by Eurofound, the European Foundation for the Improvement of Living and Working Conditions.

The study is conducted by Technopolis Group, between May 2016 and July 2017. The study team would like to **thank** the interviewees (Appendix B), workshop participants (Appendix C) and our clients and sparring partners at Eurofound (Enrique Fernandez, Eleonora Peruffo, Donald Storrie, Ricardo Rodriguez Contreras and John Hurley).

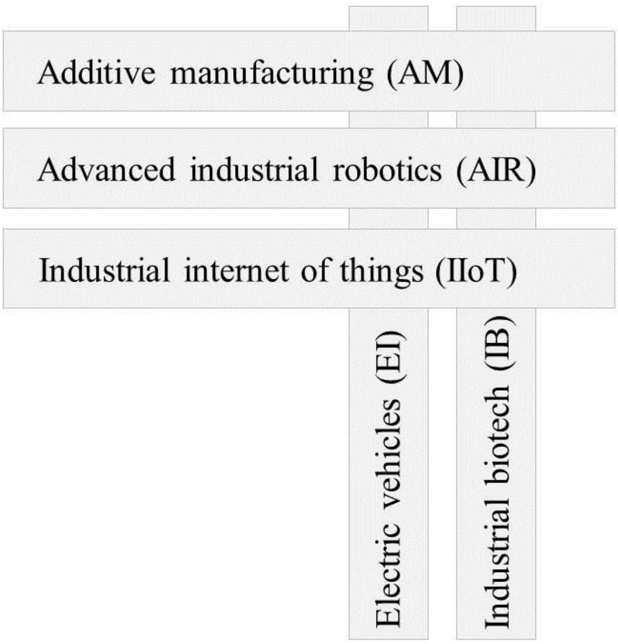
Five game changing technologies

This report is about the impact of **Additive manufacturing** (AM) and the underlying technologies on European manufacturing industries. In theory, AM can be applied in all manufacturing industries. The same applies to two other technologies addressed in our study about game changing technologies: Advanced industrial robotics (AIR) and the Industrial internet of things (IIoT). These three technologies are at the heart of industry 4.0. They influence or redefine manufacturing processes and often also have an impact on products, e.g. customisation and enabling new product-service bundles (also referred to as servitisation).

In addition, the study addresses two technologies that are relevant for a smaller set of industries and products: Electric vehicles (EV) and Industrial biotechnology (IB).

Figure 1 visualises how the three cross-cutting technologies are relevant for Electric vehicles and Industrial biotechnology (and many other industries or products).

Figure 1: Five game changing technologies



Source: Technopolis Group, 2017

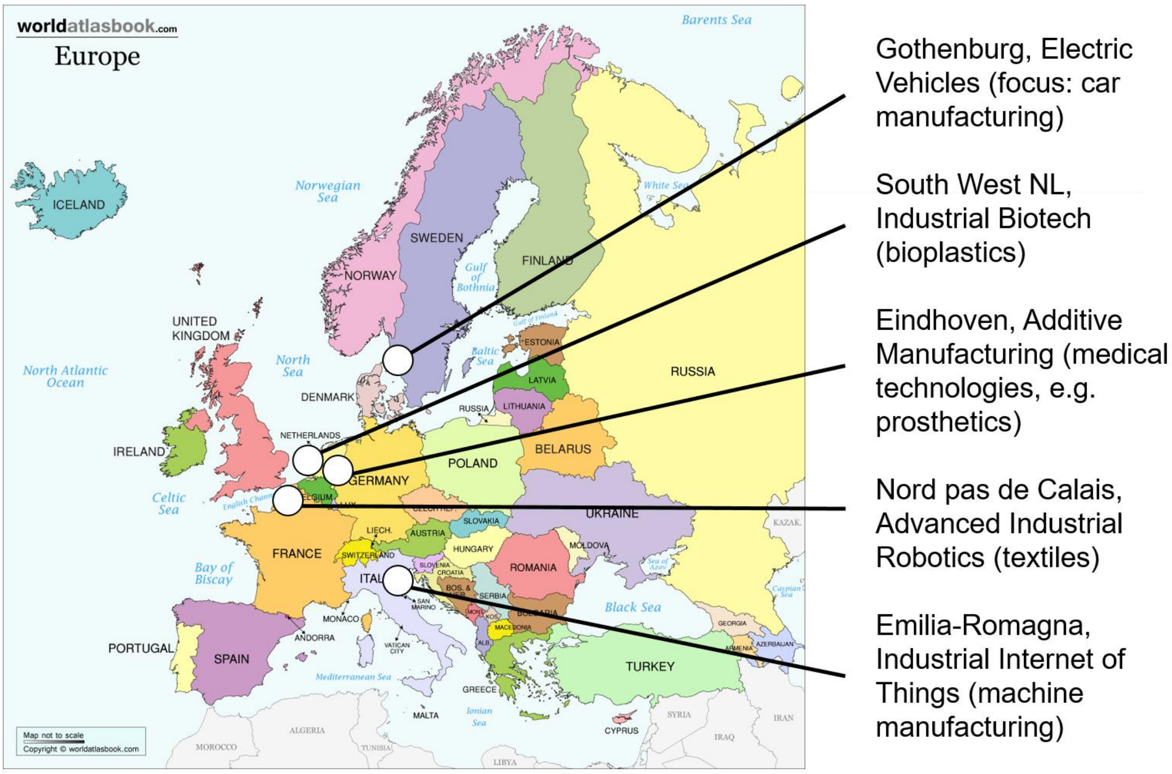
Research methods used

The study started with a **structured literature review**. Because the phenomena studied are quite recent, we used academic articles but also grey literature such as reports prepared for policy makers and industry associations and reports prepared by consulting firms. The Scopus database and Google Scholar were used to identify articles/reports with key words such as the five technologies and industry 4.0 combined with key words such as value chains, jobs, tasks, working conditions and social partners. The emphasis was on publications from 2013-2016 but in some cases older publications had to be used to fill white gaps (e.g. publications related to the impact of technologies on work). Using ATLAS.ti software and a coding scheme, relevant statements about drivers, barriers, industries affected, changes in tasks, etc., were coded and counted. The full bibliography is available upon request. Appendix A contains the sources that are used for preparing the report about Additive manufacturing.

Subsequently, 30 leading experts were **interviewed**, covering the five game changing technologies as well as specific backgrounds (such as industry, research and policy). A detailed questionnaire was used, to ensure that the three main parts of the study were covered (in short: technology, production process and work). Appendix B contains the list of interviewees that addressed Additive manufacturing.

The third and final step consisted of **five regional case studies** (one for each technology) with companies, researchers, cluster organisations and other stakeholders. In four cases, a workshop was organised. The case study about Industrial biotechnology relied on stakeholder consultation during a conference and a small scale-event. Figure 2 introduces the five regional case studies:

Figure 2 Five regional case studies



Source: Technopolis Group, 2017

The workshops were effective for validating the findings of the literature review and interviews; for filling white gaps; for providing real-life examples of technologies being tested or implemented by companies; and for discussing responses by social partners.

Outline of the report

Next section addresses Additive manufacturing, the underlying technologies, and the adoption in specific industries. The following ones explore the impact on production processes and address the impact of these changes in production process on work and mentions examples of responses of social partners. The final section concludes.

Annex A contains the detailed set of research questions. Annex B and C list the interviewees and workshop participants, respectively.

Characteristics and adoption of Additive manufacturing

Additive manufacturing is old but uptake is accelerating

Additive manufacturing (AM) is the process of manufacturing objects by adding material in precise locations to form an object, based on a digital 3D model (TNO, 2014). Adding material precisely where it needs to be is an essential difference from subtractive manufacturing methods commonly used today, such as milling (European Parliament, 2015b). A more advanced future feature of AM is that different materials can be supplied by the machine to the locations desired during a single process run, which means that alternations or even gradients of materials can be produced. Many sources report on the (potential) benefits of AM, among which unrivalled geometric freedom of design, near 100% material usage, and short lead times. Moreover,

> *"The revolution is not additive versus subtractive manufacturing; it is the ability to turn data into things and things into data." (A.T. Kearney, 2015, p. 2)*

AM provides opportunities such as rapid prototyping, advanced geometries, full customisation, local production and a lower environmental footprint. Therefore, AM yields high expectations in various engineering disciplines and in industries, in particular aerospace, automobile and medical industries.

The technologies that form the basis of Additive manufacturing have a very long history. For example, the European Commission (EC) already started supporting its technological development in the 1980s, via its Framework Programmes (European Commission, 2014b). At that time, the first AM patents were filed in the US. Substantial growth of revenues and the number of filed patents happened around the years 2009 to 2011 (TNO, 2014). The number of Google searches on the topic of 3D printing grew rapidly from 2011. This is an indicator in the so-called 'Gartner Hype Cycle' for emerging technologies. It shows that 3D printing was not mentioned as an emerging technology before 2009, while in 2013, several types of 3D printing emerge in the Cycle including 'Enterprise 3D Printing'. Many sources point towards very fast developments from around 2010 on (Deloitte, 2015; Manyika, 2013; McKinsey, 2015; Scott, et al., 2012).

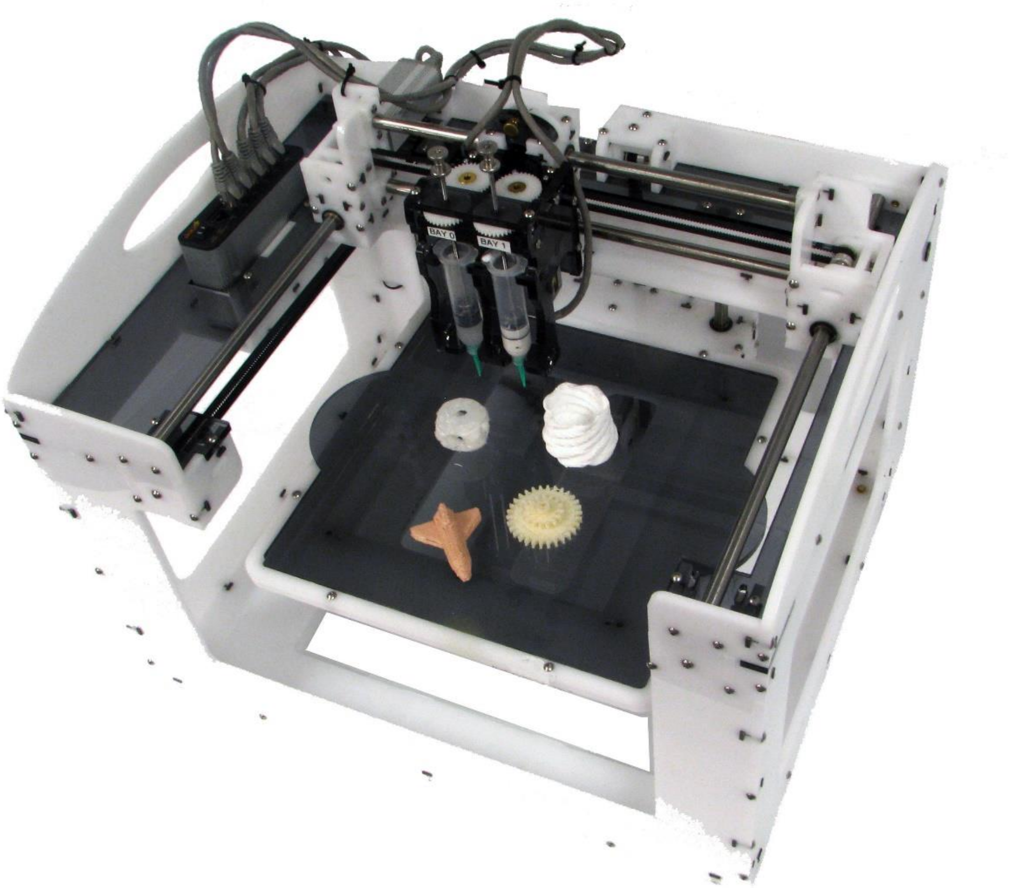
It is certain that Additive manufacturing will grow rapidly in terms of AM industry (including parts of traditional industries), market size and variety of applications. Estimates of the global AM industry vary from $1.7bn (Roland Berger, 2013) to as much as a $500bn turnover per year (Manyika, 2013). Indeed, AM has been showing double digit growth the last few years (McKinsey, 2015) and is rapidly maturing in terms of reliability, applicability and affordability.

Additive manufacturing has, in recent years, been addressed more prominently in EU policies. For example, the European Commission has highlighted 3D printing as a key element for the new Industrial Revolution in its Industrial Policy Communication (European Commission, 2014a). Horizon 2020 specifically calls for initiatives related to Additive manufacturing technologies, while roadmaps and research agendas are actively being maintained (SASAM, 2013).

AM enables total design freedom and local, flexible production

As the name suggests, Additive manufacturing is based on adding material to a substrate based on a 3D model instead of the removal of material as is classically done in for example milling (e.g. computer numerical controlled milling). A range of technologies for AM exists, each specific to for example the material used or the quality or size of the object desired. Figure 3 displays a consumer model 3D printer.

Figure 3: FAB@Home 3D printer



Source: Wikimedia Foundation, 2017

The image shows that the device is able to manufacture:

- Hollow or arching geometries;
- Multiple objects with varying models in the same run;
- Using multiple materials; and
- Only within a constrained operating dimension.

The implications of these capabilities are vast (European Commission, 2014b; Acatech & Forschungsunion, 2013a; Foresight, 2013; McKinsey Global Institute, 2015; United States International Trade Commission, 2014; UK Commission for Employment and Skills; AM Platform, 2014). Additive manufacturing opens the door to:

1. **Mass customisation**: Because AM produces objects based on 3D model data, designs can easily be adapted and customised to specific needs. The data-oriented nature also opens the door to massive-scale co-creation (online and offline).

2. **Complexity for free**: Traditional manufacturing often relies on product assembly by means of manual and/or robotic handling. Because AM can drastically reduce the need for assembly, there is no added penalty for complexity. This both lowers the costs for complex products and enables designs that were not possible with traditional technologies.
3. **Design for function**: AM allows users to design for function rather than for manufacture. This allows internal features that would be impossible to produce using conventional manufacturing techniques. Cooling channels in motor equipment and heatsinks, that feature many hollow and arching geometries, can now be designed for maximal effectiveness instead of manufacturability.
4. **Shorter time to market** for new products. Prototyping, manufacturing line setup and product adjustments are made easier as much shorter iterations between design, testing and producing can be realised and the need for process planning is reduced (United States International Trade Commission, 2014). Reducing the impact of the risks for design errors speeds up the time to market of (innovative) new products.
5. **Supply chain simplification** by instant local production reduces the number of supply chain steps and inventory sizes. It reduces the time for delivery of products, the transport and logistics required and will drive local manufacturing.
6. **Waste reduction** through the eradication of the need for material removal is expected to have significant cost savings in both environmental and economic terms. This depends on the type of AM technology applied though, as support materials and rafts can consume material that does not make it into the end product.
7. **Less pollution**: AM does not spread additional toxic chemicals in any measurable amount (though the deposited material itself may diffuse through production rooms), in contrast to traditional machines and production processes.

These capabilities are inherent to the technology itself rather than (skills of) the operator (Manyika, 2013).

The characteristics of AM mean that **entry barriers** in manufacturing industries are being decreased Because of AM, many start-ups, companies that previously shied away from manufacturing or even individuals can start producing components and products entry (Deloitte, 2014). This also due to the rapidly decreasing costs of AM equipment (Royal Academy of Engineering, 2013) and lower capital investments as well as lower variable costs as compared to traditional manufacturing methods (A.T. Kearney, 2015). Because of these properties, AM is said to be disruptive in nature with the potential to support new ideas and methodologies developed outside ‘conventional’ industry norms (AM Platform, 2013).

Despite the disruptive nature of the technology, a critical note must be made that AM is **not a plug-and-play technology**. Care for design and manufacturing line setup are essential to build quality, which in itself requires experience and knowledge. Thus, AM does not simply deliver the instant democratisation of production to anyone; it still requires capital, experience and know-how. Combined with its technological immaturity (for many materials and types of products) and its inability to provide mass production, we see that Additive manufacturing is currently employed in selected industries.

Too expensive for mass production, very welcome in high value added products

As mentioned above, the technological characteristics of Additive manufacturing very well suit small batch-production. Mass production is not a foreseen application area for Additive manufacturing. Indeed, AM is still **more expensive** than any other traditional production method, most notably injection moulding in the case of plastic or casting in the case of metals. But where small batches, customisation or highly demanding geometry dominate, AM is being adopted rapidly. We see the advent of AM in selected industries where the following aspects dominate the choice of technology:

- Batch size;
- Customisation;
- Design complexity;
- Weight; and
- Drastic assembly reduction.

Economic and strategic considerations are the main **drivers** for the adoption of AM despite the high investment and marginal costs. Environmental, legal or other motives do not seem to play a role, especially when AM is compared to Electric vehicles and Industrial biotechnology. As an immature technology in some respects, AM exhibits slow build rates which causes machine costs to be 50% of product costs. Also, process complexity (design, material choice) and the limited component size combined with high costs (most specifically for metals) are mentioned as a barrier (Roland Berger, 2013 ; United States International Trade Commission, 2014)

Still, large and small enterprises are investing in and experimenting with the technology. Mergers and acquisitions follow up each other in rapid pace in both the hardware and software segments of AM. Manufacturers are afraid that a slow start would mean lagging behind or even dropping out of competition at a later stage. Therefore, companies decided to accept the high costs of technological immaturity, when procuring and installing AM production systems (and of actually producing). In fact, interviewees noted that some manufacturers ordered several AM machines that have high idle running times, because the organisation is not yet aware how to put them to actual use.

Overall, there is a high degree of confidence in the rapidly increasing performance of AM technology and the increasingly broad range of materials at lower prices (Manyika, 2013; SASAM, 2013). This development is in part due to the open source implementation of 3D printing after expired patents (Scott, et al., 2012). More patents are to expire soon (Manyika, 2013). The prospects of reduced labour, materials and energy input as significant cost advantages, further increase the interest in AM (Kianian, Tavassoli, & Larsson, 2015).

Governments to invest heavily in AM as they clearly see the benefits, not least in the possibility to reshore manufacturing activities (European Commission, 2014a; SASAM, 2013; United States International Trade Commission, 2014; UK Commission for Employment and Skills). Many public-private-partnerships exist to drive developments and applications (European Commission, 2014b).

The most significant **barrier** is a lack of standards, interoperability and certifications for machines, materials, products and processes (Roland Berger, 2013; United States International Trade Commission, 2014; Royal Academy of Engineering, 2013). Particular aspects are quality verification standards and machine equivalence standards (Scott, et al., 2012) and process stability to aspire to ‘right every time’ production. However, a roadmap and standards are underway (SASAM, 2013). A related barrier is the lack of information on material performance (United States International Trade Commission, 2014) and information about application niches and benefits (databases therefore) (Scott, et al., 2012). The closed source nature of some AM machines and materials causes non-transparency and uncertainty about the performance of AM across different suppliers of AM equipment and materials (United States International Trade Commission, 2014).

Creating 3D designs is still a limiting factor. Computer Assisted Design (CAD) tools used for creation and optimisation of models for 3D production, are designed for subtractive manufacturing instead of AM. As such, these CAD tools are not capable of fully using the freedom of expression in AM or interconnecting multiple AM machines for multiple process steps (Royal Academy of Engineering, 2013; Scott, et al., 2012). Moreover, a lack of 3D design thinking prevents mass adoption (A.T. Kearney, 2015). A 3D scanner is a possible solution for one part of the design challenges, at least for copying existing products. 3D scanners are becoming less expensive and easier to use (Scott, et al., 2012). For example, smart phones, game consoles and other consumer electronics have been employed as 3D scanners (Manyika, 2013) and scanning and design software and technology are catching up with AM adoption (United States International Trade Commission, 2014). Related to design, are legal and regulatory considerations of Intellectual Property Rights (IPR) on goods, products or models; liability in case of design or production failures; customs duties (on imported model or product?); and value added tax (Deloitte, 2015).

In short: AM is evolving rapidly (Cohen, Sargeant, & Somers, 2014) with diverging Technology Readiness Levels (TRLs) depending on the technologies and material used. There are studies that indicate that AM for simple plastic parts is already economic for US households (Deloitte Review, 2014b). Machine costs and software limitations are likely to be resolved in the medium term (5-10 years) as multiple design tools are proliferating. Material choice and quality are currently very limited compared to traditional manufacturing, but this has improved rapidly the last five years (United States International Trade Commission, 2014). Some experts predict that AM will be mainstream in some industries well before 2020 (Weller, Kleer, & Piller, 2015). Other experts are less optimistic and note that it could take more years before the impact is felt beyond a limited range of goods (Manyika, 2013).

Box 1. Cost-efficiency as a driver for reshoring hearing aid production

One highly demanding application of AM for customised prosthetics is hearing aids. Because of an ageing population in Europe, demand for hearing aids has been rising since the late 1990's. Hearing aids need a very good fit within the ear for comfort as well as performance. Because of the complex geometry within and the large variations between human ears, they used to be hand-crafted in a production process with as much as nine steps, together requiring over one week and most of them involving manual labour. Due to its labour intensity, the production of hearing aids was offshored to low-wages countries.

With 3D printing, the production process was drastically simplified, eradicating most of the manual labour. This not only reduced the production costs but also the production time. Because manufacturing time reduced drastically to within several hours, the shipping time to the consumer market became much larger in relation to the production time. Because labour was no longer a big factor and to eradicate shipping delays, local production in Europe became a feasible choice. Producers first applied 3D printing in the high-end models to allow for experimenting and failure rates, because of high prices.

As of 2017, most European hearing aids are produced in Europe with higher quality, lower price and shorter delivery period: a combination that is considered quite impossible in project management theory, made possible by Additive manufacturing in less than a decade.

Source: https://arcadvisorygroup-public.sharepoint.com/myarc/myreports/arcreports2013/Healthcare%20Industry%20Benefits%20from%20Additive%20Manufacturing.pdf

AM finds applications in automotive, aerospace and medical industries

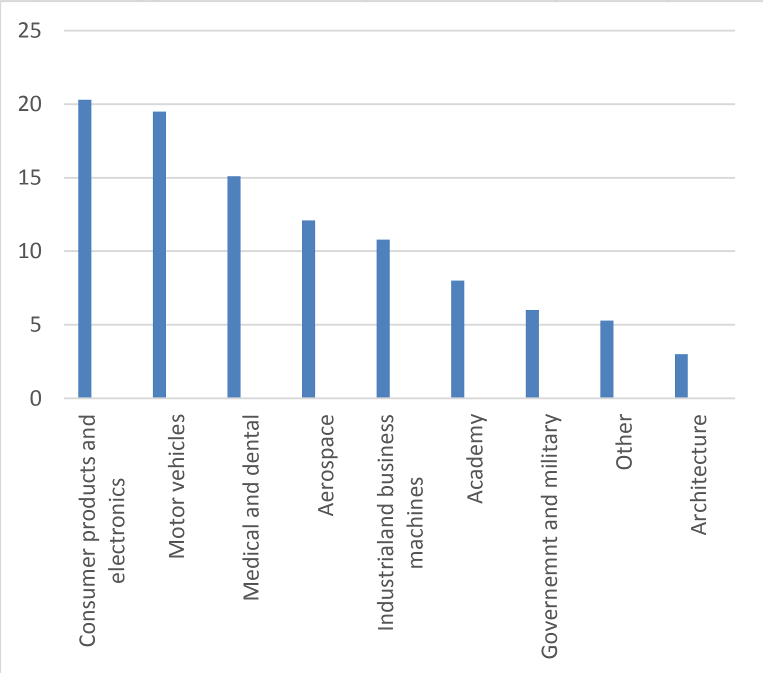
AM as a manufacturing method can be applied in any industry where tangible goods are produced, but the actual case depends on **trade-offs** between size, quality (in terms of accuracy and durability), speed and cost (United States International Trade Commission, 2014). AM technologies exist for all materials, including metals, plastics, ceramics and even living cells (Deloitte, 2015). Currently, the main challenge is to ensure that AM allows for aligning with the trade-offs between batch size, customisation, design complexity, weight and assembly reduction that are accepted in specific industries.

Traditionally, AM has been applied in industries where **prototyping** and **visual designs** are important as a for rapid prototyping. Most prominently, this concerns architecture, construction, automotive and aerospace industries. As AM technology develops, it is increasingly used to supply the 'live parts' in these industries and beyond (UK Commission for Employment and Skills).

The application of AM in specific industries is influenced by very specific factors. For example, AM can make a big difference in processes with high scrap rates, i.e. those where a lot of material is currently wasted in milling or subtraction processes (Scott, et al., 2012) and those with high obsolescence (Cohen, Sargeant, & Somers, 2014). Industries that favour lightweight items (Roland Berger, 2013) and flexible or conformal electronics (that follow the shapes of the product's design) (Scott, et al., 2012) also benefit from AM.

Figure 4 provides an overview of AM applications in various industries.

Figure 4 Application rates of AM in 2012 by industry



Source: Adapted from AM Platform (2014)

The discussion above is based on literature and is confirmed by our interviews and workshop. Of the automotive, medical and aerospace industries in the US, respectively, 19.5%, 15% and 12.1% of the companies applied AM in 2014. Figures for the EU were not available but literature and interviews point to the same three industries.

The **automotive industry** has been using AM for decades because of their intensive use of prototypes and is now moving to produce 'live' lightweight parts from aluminium alloys (United States

International Trade Commission, 2014). The automotive industry can also gain from AM because of the importance of customisation as one of the means to avoid price competition (Foresight, 2013).

The **aerospace industry** has much to gain from AM, too. Both Airbus (Scott, et al., 2012) and Boeing (Manyika, 2013) use AM to produce 50-80% lighter parts for their airplanes. This pays back in fuel economy. Other sources mention the ability to reduce material consumption by 90% and weight by 30-55% (Deloitte Review, 2014b; A.T. Kearney, 2015; Brettel, Friederichsen, Keller, & Rosenberg, 2014; Foresight, 2013). Specific applications are those for fuel injectors for jet engines which are very labour intensive to produce. General Electric intends to apply AM for half of the parts in their energy and aircraft turbines. This example is often mentioned by experts in the industry, including our interviewees. In rocket engines, a cost reduction for the most complex parts of up to 70% is possible. So is a production time reduction, from twelve to four months (United States International Trade Commission, 2014).

The **biomedical industry** is also one of the large adopters of AM because patient applications can require a high degree of customisation. Specific applications are mentioned in prosthetic limbs (United States International Trade Commission, 2014), dental implants (Deloitte, 2014a) and even tissues and organs (Foresight, 2013).

Other industries mentioned are architecture, construction, defence, aerospace, power generation, jewellery, shoes, home accessories, fashion and entertainment and the creative industries in general (Foresight, 2013; Deloitte, 2014a; A.T. Kearney, 2015; Royal Academy of Engineering, 2013; Scott, et al., 2012; Weller, Kleer, & Piller, 2015; AM Platform, 2013). Furthermore, AM has the capability to produce complex mechanisms, batteries, transistors and LEDs (Cohen, Sargeant, & Somers, 2014). Finally, the production of small consumer items such as phone cases through services like Shapeways (Manyika, 2013) deserves a separate mention as it displays already the democratisation of design and the transformation of business models.

Technology maturity and production costs vary specifically over the **type of material** and **build speed** required. For plastics, the technology is very mature and consumer grade 3D printers are available for less than €500 (Manyika, 2013; Thomas & Gilbert, 2014; United States International Trade Commission, 2014). For other materials, most notably metals and ceramics, it is harder to use AM while meeting quality and other requirements. A specific example is biomedical implants and prosthetics. Organ printing (using living cells) is far less advanced than for example prosthetics (using plastic) (United States International Trade Commission, 2014; Foresight, 2013; Cohen, Sargeant, & Somers, 2014).

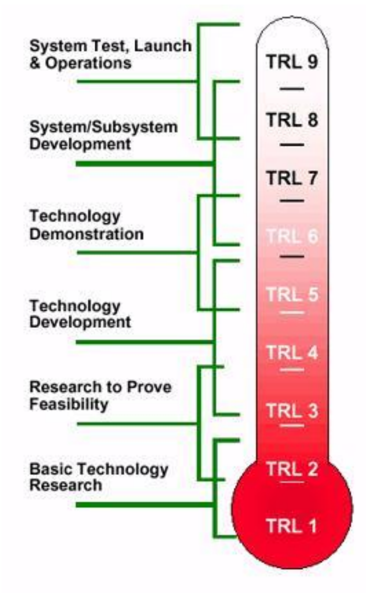
Sintering is coming up as metal deposition technology (Royal Academy of Engineering, 2013) and is on the verge of maturity in the aerospace industry. (Roland Berger, 2013). However, for most industries the statement holds that hardware must improve to succeed with complex items (A.T. Kearney, 2015). For mass-produced goods, AM is nowhere close yet compared to the traditional manufacturing industry (Royal Academy of Engineering, 2013).

A summary of **Technology Readiness Levels** (TRLs)[2] of AM technologies and materials is as follows (AM Platform, 2014).

- Many types of AM are in the 'productionisation' phase; applications have been developed and are awaiting exploitation. This would equate to approximately TRL 4.
- The AM of plastics is, in general, at a higher TRL scale (TRL 7-9) than that of metals (TRL 3-7). However, the additive manufacture of plastics with good engineering properties is generally lower (TRL 4-5). Other materials are generally lower than this (TRL 1-3), for example ceramics.
- The majority of AM types considered for aerospace manufacturing are around the TRL 4-6 level, with specific 'secondary' issues facing the final deployment.
- Repair and servicing for the aerospace industry is a high value-added activity and is readily applied in production (i.e. TRL9). This activity would be greatly assisted by high-precision reverse engineering capabilities to duplicate a component and determine repair requirements. Technologies to assist this are currently at TRL 5-6.

Note that this concerns indications only. Moreover, the TRL of specific technologies and materials can change quickly.

Figure 5: Brief overview of technology readiness levels



Source: Wikimedia foundation

Gradually, AM will be applied in more and more manufacturing industries. As mentioned above, injection molding still is far more competitive for mass production than Additive manufacturing. But the moulds themselves can be very well produced using Additive manufacturing. This allows more frequent and easier adoption of shapes. Interviewees mentioned such examples.

[2] Technology Readiness levels or TRLs are used to assess a technology's status with uniform criteria. TRLs have nine stages, from 1 (basic principles described and observed) through 5 (laboratory testing) to 9 (ready for full scale deployment).

Impact on production processes

AM enables flexibility throughout the value chain

Mass customisation and co-creation through AM is said to be a pivotal element in the upcoming democratisation of production (Royal Academy of Engineering, 2013; Scott, et al., 2012). This can enable business models such as platforms for sharing and connecting product designs and designers alike in a sense of co-creation (Cohen, Sargeant, & Somers, 2014; A.T. Kearney, 2015). Others note that business models that employ mass customisation are not yet ready; considerations as to the freedom of choice allowed are not yet boiled out (United States International Trade Commission, 2014).

Customers can be more involved in the production process through product 'copy shops' instead of standard shops. (Acatech & Forschungsunion, 2013a). Because consumers can make their own products (Brettel, Friederichsen, Keller, & Rosenberg, 2014), manufacturers of simple consumer products need to find ways to match the advantages of home production (Manyika, 2013, p. 113):

> *"Access to 3D printing could actually make some manufacturing sectors more competitive. For industries with high-value goods, in which rapid innovation is more important than absolute cost, the combination of 3D printing of products and advanced robotics [...] could make proximity to end markets and access to highly skilled talent more important than hourly labour rates in determining where production is located. This could lead some advanced economy companies to produce more goods domestically, boosting local economies. However, this may not create many manufacturing jobs, as the 3D printing process is highly automated."*

This comment leads to the second impact on business models:

Extreme supply chain simplification and inventory reduction are enabled by AM. Our literature indicates that distributed local and global supply chains will emerge, with manufacturing done closer to the point of consumption (Foresight, 2013; Cohen, Sargeant, & Somers, 2014; Deloitte Review, 2014b). This will certainly be the case when delivery costs overpass production costs, due to higher maturity and lower costs of AM machines and materials. AM enables inventory reduction through instant production and reduces the need for intermediaries. Spare parts can be produced on site and the reliance on highly specialised suppliers can be reduced (Deloitte, 2015; McKinsey, 2015; Brettel, Friederichsen, Keller, & Rosenberg, 2014; Foresight, 2013) (Manyika, 2013). Several authors predict the first applications of this business model of small 'fabs' on sites such as airports and hospitals. (Cohen, Sargeant, & Somers, 2014). Interviewees mentioned similar examples.

Radically different economies of scale stimulate new entrants and innovation through shorter time to market and lower production costs (Cohen, Sargeant, & Somers, 2014). AM is said to lower market entry costs and open markets for new entrants (Cohen, Sargeant, & Somers, 2014; Weller, Kleer, & Piller, 2015). Concepts like **bridge manufacturing** emerge, where AM precedes large scale manufacturing for the first orders while larger batch manufacturing is still being set up. This can be very beneficial for the cash-flow of start-ups and other small enterprises.

Reduced transport demand is an obvious outcome of AM developments (Scott, et al., 2012) and the combined manufacturing energy and transport fuel requirements can drop as much as 85% (Deloitte Review, 2014b).

AM is slashing **tooling times** and **the demand for subtractive manufacturing** (Cohen, Sargeant, & Somers, 2014; Deloitte Review, 2014b; Scott, et al., 2012; Roland Berger, 2013). Because subtraction is strongly reduced, so is the material demand (Cohen, Sargeant, & Somers, 2014; Brettel, Friederichsen, Keller, & Rosenberg, 2014; SASAM, 2013; United States International Trade Commission, 2014). The reduction in demand for both materials and equipment is illustrated by the following statement: "*Sometimes we machine away 90% of the materials to create the final* *component, but with AM that figure is much reduced*." (Royal Academy of Engineering, 2013, p. 10). The same source notes that consumers may be increasingly wasteful as they can easily print a new product when the old one breaks down, either because of bad design, changing taste or material degradation.

Equitable metrics for measuring the environmental impact of AM are needed. To date, few studies have examined the variety of environmental impact of Additive manufacturing. Potential benefits over conventional manufacturing include the following (Scott, et al., 2012, p. 12):

- Efficient use of raw materials/feedstock as compared to conventional processes that often start with a solid billet of material, which is then machined down to specifications. When machining parts, scrap rates can be as high as 80-90 percent. Using Additive manufacturing to produce the same part in metal reduces the scrap rate to 10 percent or less.
- Displacement of energy-inefficient processes such as casting and computer numerical control (CNC) machining to reduce environmentally unfriendly fluids and metal debris.
- Reduced need for fixed asset tooling as manufacturing shifts to more adaptive processes that require fewer pieces of specialty capital equipment.
- Lighter parts as a result of complex structures and concomitant transportation and fuel efficiencies.
- More efficient heating or cooling channels, fluid paths, and other internal features that are not producible using conventional techniques.

Box 2. From Addlab to Addfab: Industry collaboration for collective learning

The adoption of AM by companies comes with many uncertainties and high investments. Manufacturing companies acknowledge AMs importance and potential but need hands-on experience to see how and where to apply the technology.

To reduce risks and share the burden, AddLab was established in 2013 by nine collaborating partners from the manufacturing industry in the Eindhoven region. In the collaboration, there was room for 20 manufacturing engineers to train and experiment with the technology, while companies could assess performance and learn where to apply the technology. Three years later the collaboration was continued with three partners and moved to a larger location.

Jeroen Jonkers, one of the partners' design engineers, explains: *"We have explored all the relevant aspects of AM, for a large variety of products, materials, applications and post-processing options. We have solved many issues and now have a clear perspective of the possibilities. Individually, the partners could not have reached this level. Now, in AddFab we want to refine our knowledge and extend our experience to industrial applications.*"

Furthermore, the initiative was extended towards software developers and education. According to the founders, the initiative can now begin to generate turnover besides knowledge and experience.

Source: http://use.zerniq.nl/upload/www.addfab.nl/publications/Mikroniek--van-AddLab-naar-AddFab.pdf

AM creates and enables new and higher demand throughout the value chain

Additive manufacturing processes and equipment vary strongly per applied material, as each class of materials (plastics, metals, ceramics, bio-materials and others) requires different AM equipment. But as manufacturing processes for different materials mature, the processes are adopted in higher numbers and as such the **demand for the input materials rises**.

One must note that where AM processes replace traditional processes, there is a substitution of materials. Metal printers for example do not take the same metals that are used in casting or milling processes; often they use specialised powders from alloys and oxides. This holds too for polymers, while for biomaterial printing there is no substitution effect. In the case where specialty polymers, alloys and oxides replace bulk materials, there is an equal rise in demand for specialised production processes of these alloys and oxides. It depends on the specific case if these are more knowledge or capital intensive to produce or not, but we may thus see a shift of value added towards earlier steps in the production chain, too.

A similar development can be perceived beyond the AM process in the production chain. The adoption of **auxiliary equipment** for AM will grow proportional with the adoption of AM. Such equipment is used to remove finished products from the build platform and place them in a new AM machine, due to the batch production nature of AM. Other auxiliary equipment is for example used to remove support structures or to post-process the outputs in other ways.

Similarly, the demand for pre-processing products will rise with the adoption of AM. This is mostly on the **software** side. In this respect, developments in the design tools are highly anticipated, but also (and perhaps even more so) software that translates the design in actual machine commands can see rapid developments and uptake.

Interviewees and workshop participants mentioned interesting examples of **supply chain digitisation**. Owing to the digital nature of AM and the piece-wise manufacturing, large customers such as aircraft producers can increasingly influence the production demands and the methods employed by its suppliers. Already they apply certain supplier certification schemes, and interviewees mentioned the future scenario that the customer presses the manufacture button at its supplier when the need for parts arises.

With multi-material printing, a combination of all developments mentioned above will drive demand for special machines, materials, auxiliary equipment and software.

Shorter product cycles, more incremental design and digitized production

AM enables not only rapid prototyping easier but also **frequent adaption of products and product designs** through continuous quality management (Deloitte, 2015; Foresight, 2013; A.T. Kearney, 2015). As noted, design and engineering may become crowdsourced themselves, such that management of the crowdsourcing process becomes the main value added activity (Cohen, Sargeant, & Somers, 2014). Through the strongly reduced demand for assembly and tool operation, work processes can become simpler.

AM is by essence a digital and data-driven method, with the work process migrating **from the floor to the screen** (Deloitte Review, 2014b). Interviewees add that, through the increased flexibility of AM, the machines can be switched off more often than traditional industrial machines. This means that the work process and schedule are no longer dictated by (minimising) idle time. This has implications for working shifts and hours. Workshop participants contradicted this finding, as common sense economics dictate that production capital will always be used to the maximum extent. Because of the reduced amount of production steps, idle time between switching machines is reduced too. This means that operators may have to face a more monotonous job or can take fewer breaks. At least, their work rhythm will be similar to their rhythm in other types of factories (McKinsey, 2015). Interviewees and workshop did notice ways in which the work of process operator can be diverse. Because products delivered by an AM machine are usually far from finished, the operator may as well be tasked with (parts of) the finishing process and (un)loading, such that they get a responsibility for a larger portion of the total production process.

The **time lines for changes in work processes** are heavily influenced by the timing of increased technology maturity and adoption of AM across industries. As mentioned above, many changes are expected between 2017 and 2020. As design tools and 3D scanners become more advanced, work processes can become more digital and more streamlined, with less demand for physical tasks ‘on the floor’. Intellectual and social tasks will become more important, for example when designing and improving products. These changes will depend on the level of integration between AM, Advanced industrial robotics and Industrial internet of things. Interviewees and workshop participants stress that robotics is the main factor that influences work processes.

AM can expand on a per material basis and drive manufacturing efficiency

Long term predictions on the progress of what is widely recognized as a disruption are usually not precise and rarely accurate. Literature and interviewees rarely leave the safe path of **extrapolations** and if they do, they precede any claim with that it is a speculation.

As mentioned above, there is no such thing as 'the' Technological Readiness Level of AM. We have seen that Additive manufacturing technologies differ per material, and that AM relies on hardware, software and feedstock improvements to improve.

We have noted that in principle all materials can already be used for Additive manufacturing, and that the difficulties are in the costs and standards of machines and materials, the failure rate of machines and products, and the software for both product design as well as production process integration. Incremental progress in these areas will lead to more reliable production of an increasing range of materials, with more time needed to develop and apply multi-material Additive manufacturing.

Once the properties of AM are below a certain **cost threshold**, we may see radical shifts in the adoption of AM akin to the progress in automotive, aerospace and medical industries. Technological advancement means this process can reiterate itself over an increasing range of industrial sectors, probably on a per-material basis. Mono-material, mass production will probably remain the realm of other manufacturing technologies.

This is not to say that these manufacturing technologies and the industries that use them are not affected. AM will enable **shorter design-production cycles** through rapid prototyping and bridge manufacturing. This supports a more experimental approach (akin to the *agile* approach used in software development) to product design and marketing. With shorter design-production cycles, cash flow restrictions for new entrants are reduced and so this will democratize production to some extent.

The role of AM in traditional manufacturing is also displayed in maintenance and spare parts. Certainly, when combined with predictive maintenance enabled through the Industrial IoT, AM should be able to decrease downtime and repair costs of traditional industries and so increase the efficiency.

Impact on work

Product responsibility and process responsibility

Given the (still) relatively low adoption rates of Additive manufacturing in industry, there are very few studies about the impact of AM on work. In our interviews and workshop, experts and practitioners were able to discuss preliminary and expected effects of AM on work. This includes concrete, real-life examples. This section discusses possible effects on tasks and skills needs. An overarching theme is that the different tasks along the production process become more entangled, instead of being organised into discrete steps such as manufacturing and assembling components.

Section 4.2 will address how changes in tasks may also lead to new occupations and to existing occupations being changed or (in some cases) becoming less needed. Section 4.3 elaborates on working conditions. Section 4.4 discusses education and training.

Tasks

Our literature review indicates that changes in **social tasks** will become more important due to AM. Team work is no longer confined to individual steps of the production process, but also concerns closely linked steps such as design, material and process engineering, process operations and post-processing. Moreover, collaboration with external designers and material engineers and providers is expected to increase. Multi-disciplinarity becomes more important. However, interviewees and workshop participants stress that team work has always been an important factor in successful production environments. The point about multi-disciplinarity was underlined.

AM is said to decrease demand for **manual tasks** such as assembly by as much as 67% (Deloitte Review, 2014b) through part simplification (Roland Berger, 2013). Others mention that AM will reduce the demand for labour in general (Kianian, Tavassoli, & Larsson, 2015).

AM requires a workforce that is adept on analysing vast quantities of data and focusing on design and quality management (Foresight, 2013). The experts that we consulted agreed that the increased importance of IT, data and creativity leads to more **intellectual tasks**. Regarding the role of data, experts referred to the combination of AM and the Industrial internet of things.

Increased IT and data intensity, possibly more team work or more multi-disciplinary teams and less manual labour, also has implications for **managers**. The departments or activities that they oversee, and the staff they facilitate, will become more diverse yet entangled. Interviewees mentioned that managing AM may have similarities with managing creative industries, IT companies and traditional manufacturing companies.

New tasks will emerge like **loading** and unloading machines, filling material into the production machines and removing (support) material from the fabricates. This may become a job in itself, though machine unloading will probably be soon automated as some products (metal car parts) can become rather heavy.

Skills

As can be expected, literature and experts agree that AM requires **process engineering skills**, **material/resource** specific skills (such as material engineering and chemical engineering) and **equipment/machinery operation** skills. The literature review that changes in skills needs will just as substantial for machine operations as for **management**.

Engineering skills are affected by the increased digitisation of production. AM relies on computer models for production even more than CNC milling, which in itself is also computer intensive. This has consequences for machine operators for example. Some argue that the need for new, electronics and IT related skills will only concern a small number of employees, because of the increased computerisation of AM machines (with sensors, actuators, computing power and displays). Machine operators could then be assisted by augmented or mixed reality solutions, such as HoloLens or Google Glass. This could imply user-friendly interfaces and less need for in-depth technical skills (‘like driving a car’).

The development and deployment of AM requires skills in **equipment design**, **material technology** and **IT**. Employees should be creative, resourceful and eager to figure things out (Deloitte Review, 2014b). Designers need to rethink manufacturing from replication to creation (Royal Academy of Engineering, 2013) with more focus on function and design rather than manufacturability (Deloitte Review, 2014b). Interviewees note that designers should become aware of AM’s (dis)abilities as compared to traditional manufacturing.

Technicians need to adapt to new techniques such as part finishing and machine calibrating, and get to know the machines, while recording and maintaining the data of the models and their adjustments. Managers need more intimate knowledge of their teams and their individual's interests as their employees’ jobs become more cross-functional in a culture of change and innovation.

From the narrative above we can conclude that the most important skills (and competences) for Additive manufacturing are:

1. The ability to see the production process in a wider context from design to finishing, through machines, materials and production steps;
2. Understand the digital nature of the production process; and
3. The ability to adapt to changing technologies, production processes and business processes for manufacturing.

Changing occupations and debates about the amount of work required

Occupations will change because AM change the content and combinations of tasks, as discussed above. Some occupations will probably disappear (for example computer numerical control miller) and be replaced by AM designer/operators. We may also see the re-emergence of old trades like repair shops. A home production revolution is not expected, though AM and open source hardware are expected to spur more local inventors, possibly through maker spaces and the maker movement.

It should be mentioned that the experts consulted, emphasise the importance of professional AM designers/operators rather than experts working in small-scale maker spaces.

The literature review indicates that there is a shift to more work in **design**, (value chain) **management**, marketing and sales. and less work/jobs in the production process as such ('the heart of the production process'). To some extent, these new jobs in the first and last parts of the value chain will be situated at new suppliers and service providers. The extent to which these jobs are in Europe, depends on whether AM and robotics leads to re-shoring, and a cycle of higher productivity and quality leading to higher sales volumes and production volumes. In short: it is impossible to discuss the number of jobs needed, without considering total production volumes.

With respect to reshoring, experts mention that European companies also locate in regions such as Latin America, India and South East Asia, to be closer to customers in these regions and, in some cases, closer to materials. Experts also mention that reshoring (or not) concerns mass-production and not the type of small batch production enabled by AM (robotics is considered to be more relevant).

Both literature and stakeholders indicate that **science and engineering professionals** are most affected by AM. There is not only a change in the way that these professionals manage and operate the manufacturing process; they also need to design, rebuild and adapt parts of the manufacturing process (and the value chain). Thus arguably, there is an increased demand for science and engineering professionals while they also need to master new AM-related skills.

Of course, **manual labour is** severely affected, too. In our study, we have not been able to find consensus. Rather, the field seems to be divided between optimists and pessimists, with both sides making compelling arguments. Though assembly tasks are likely to diminish in some industries, post processing remains necessary and the production process may still entail several steps as long as multi-material Additive manufacturing is not sufficiently technologically advanced. Moreover, one of the industry leaders consulted, mentioned that "just as the turning machinists moved to CNC milling, we expect the CNC millers to move to AM."

Depending on the extent to which AM leads to small-scale production and democratisation and localisation of production, new or restored occupations could be in local production hubs, repair shops and/or places to produce spare parts (Kianian, Tavassoli, & Larsson, 2015). Given the small scale of these activities, staff needs to possess multi-disciplinary skills **set**.

Box 3. Home manufacturing?

Reports and popular beliefs prophesize the advent of home-factories and "never having to go to a store again". Indeed, there is rapid growth in demand for consumer model 3D printers. Though home 3D printers continue becoming cheaper and more popular, Gartner reports lower growth rates and a large share of 3D printers that is actually bought by educational institutions and enterprise engineering, marketing and creative department (Gartner, 2016). Indeed, there are several arguments against a rapid growth of home manufacturing:

1. Most day-to-day household items are mass-produced and **Additive manufacturing is not fit for mass production** because of its low production speed and high costs.
2. Related to the above, household 3D printers usually print *one* type of material at the same time and practically only plastics. But especially mono-material plastic objects for household can be produced by the millions in injection-molding factories. Interviewees note that AM does not compete with injection molding in the foreseeable future.
3. In addition, **the more valuable objects in households that could be worthwhile making at home are made up of multiple materials**, including metals, glass, rubbers and varnishes. Though multi-material printers exist they usually print two kinds or colours of plastics, and home printing of metals and glass is mere speculation.
4. Perhaps most importantly, **Additive manufacturing is a difficult process** that still requires tuning for each different model produced to yield quality material comparable to injection molding. The idea that home 3D printing is a matter of "click to materialize" is still untrue and will remain to be so for the foreseeable future.

This does not mean that households and private persons will not experience a production revolution. The **maker culture** that has arisen since the early 2000's is very alive and gaining mass. But it is still a sub culture and the items they produce are highly customized, often in the realm of gadgets and custom-built technology solutions. Some compare the maker culture in which inventors thrive as **Tech-oriented DIY.** And while DIY has a very major market segment for its own, there is still a far larger construction sector.

Still, the number of **job advertisements** calling for 3D printing skills increased by 1,834 percent between August 2010 and August 2014. These 3D-related jobs mostly concern industrial engineers, mechanical engineers, software developers and industrial designers (Vazquez, Passaretti, & Valenzuela, 2016, p. 4).

To conclude this section about occupations, a **broader perspective** is provided. Industry 4.0 and, especially, the combination of AM, industrial robotics and IoT will lead to the following impact mechanisms (Degryse, 2016).:

- Job creation through new sectors, products and services;
- Job change through new forms of worker/machine interaction; democratisation and "Uberisation" (unorganised self-employment) of work; effects at managerial level;
- Job destruction through increased machine autonomy; and
- Job shift, caused by the commoditisation and increasing location-independency of, for example, design tasks.

The World Economic Forum, based on a global industry survey, confirms this rich and nuanced picture. Their report on employment trends notes that AM and related technologies can have a labour substituting effect, but this depends on the interplay with demographic trends (lower demand growth in ageing societies) and geopolitical risks of supply disruption. On the other hand, WEF notes that AM is specifically a strong driver of employment growth in architecture and engineering *(World Economic Forum, 2016).*

Cleaner and more automated environments, but hazards not yet known

Studies about the impact of AM on working conditions are scarce yet much needed (EU Trade Union Confederation, 2015). One of the concerns of ETUC it that the democratisation of production and the digitalisation of labour can lead to an increase of **small-scale production locations** without well-regulated labour conditions, among which working times and schedules and decent wages. Additionally, the degree of organisation of workers may decrease, as maker spaces and home 3D printing become more prominent. However, interviewees and workshop attendants could not substantiate these risks. Instead, they argue that AM machines are operated in an industrial environment, preferably 24/7, just as current traditional manufacturing equipment.

Several interviewees state that AM is inherently **safer** than machining and milling with CNC or lathing equipment. This is certainly true for mechanical safety, although AM also requires mechanical operations such as support structure removal and post processing may still be necessary. On the other hand, high voltage arcs and high temperature nozzles found in many AM setups are not necessarily safer than mechanical hazards. This point is mentioned by another set of interviewees.

The reduced amount of material subtraction can be reasoned to lead to cleaner working environments but evidence reporting about the occupational hazards of AM machines and materials used was not found. Thus, it cannot be said that AM is safer or cleaner. In fact, the most frequently voiced concern in literature and interviews alike is possible **material toxicity** of new compounds, for which there are no safety standards yet. Concerns are for example that there are asbestos-like risks because of small particles or the inhalation of fumes.

Unfamiliarity may also be an issue. As AM becomes embedded in existing production lines and value chains, this can lead to temporary and minor challenges related to technical integration, safety (new materials), quality control, correctly and safely conducting tasks (e.g. designers and operators) and the need for education and training.

Finally, workshop participants mention that AM may cause a **simplification** of work for those on the factory floor: removing finished products or refilling material (Thomas & Gilbert, 2014). On the other hand, these tasks may also be automated or, instead, be one of the tasks of process operators.

Box 4. Field service engineers under pressure

Field service engineers are called into action when production equipment at industrial premises requires maintenance or upgrades. FSEs, often employed by equipment manufacturers, used to be called into action when site operators at a client's production site needed inspection, repairs, upgrades or just new parts – that are often custom made for that production environment.

Remote diagnostics, enabled among others by the Industrial internet of things, has drastically reduced the need for on-premises inspections. Remote diagnostics also enables predictive maintenance which in turn reduces breakdowns and thus emergency servicing.

AM further reduces the need for travelling FSEs because custom parts can be manufactured close to the site of demand, which reduces the need to travel along with the component and subsequently install it. Finally, developments like virtual presence can assist local engineers to install the parts themselves, rather than by a travelling field service engineer.

Collaboration for education, training and lifelong learning

The discussion in section 4.1 on skills needs for AM already hinted at the need to **adapt curricula** of education institutions and to **adapt and intensify training** in manufacturing industries affected by AM. Highly specified and stable curricula and training programmes for occupations are said to be a thing of the past. Interviewees argue that students need to train for skills that most fit their interest and capacities that can subsequently be expanded by training at an employer in need of these skills. Students thus need the overview; the competences to see which skills are required and adapt their skillset to that demand. Possibly this increases the need for education/training coaching.

Based on our interviews and workshops, we see that strategies for dealing with skills needs for AM are very similar to strategies that are discussed in the context of Industry 4.0. Four key elements are:

- Increased importance of **life-long-learning** as technology becomes a larger part of the job and technology itself develops fast;
- Ensure that pupils, students **engage with technology as early as possible**, to reflect the increasing role of technology in our daily lives;
- A focus on **21st century skills** and some technical skills rather than in-depth knowledge. Knowledge about processes such as milling and CNC operations may vanish but the skills for tools programming remain useful. A special case remains for the skill to acquire knowledge and skills: 'learn to learn'.
- Increased importance of **inter-disciplinarity** because of the interaction (or even integration) of tasks such as product design, process design, process engineering, process operations and quality management.

To accommodate **lifelong learning**, workshop participants suggest that education at universities and vocational education can be shortened in time and budget by a significant fraction, where the remainder is reserved for training on the job. Others argue for a life-time education budget rather than a system in which one is most encouraged to learn between the ages 12-30. They argue that it should be extended up until the age of 70 years old.

Large scale impacts of Additive manufacturing on the manufacturing system in Europe have yet to materialise in most industries. Impacts throughout the value chain are expected, with changes in production processes, tasks, skills and competences. One of the strategies observed is to intensify **collaboration between industry and educational institutions**. Long-term, yet flexible education and training programmes are required.

Again, note that Additive manufacturing is not the only technology affecting the manufacturing industry. The industrial IoT and Advanced industrial robotics may be at least as important as AM. Also note that discussion about education and training can me mixed with **ethical and political debates** about automation. For instance, in discussions about robots one can distinguish between *technofatalists* arguing that there will simply be no jobs in the future, versus *technofantastists* that see emerging jobs such as space tour guide and human body designer (O'Connor, 2017). The experts that we consulted take a pragmatic, non-alarmistic approach when it comes to automation, education and training.

Box 5. Brainport Development's human capital agenda for the Eindhoven area

Brainport development is a foundation for the advancement of industrial development in high-tech sectors in the Eindhoven area, sponsored by municipalities, enterprises (like Philips, ASML, NXP but also SMEs) and higher education institutions. Their 2013-2020 **Human Capital Agenda** acknowledges AM and related developments and formulates (among others) the following action points:

- **Increase attention for technology in primary and secondary education** by linking STEM profiles with creative and entrepreneurial topics.
- **Increase popularity of technical education** in centres for innovative craftsmanship and centres of expertise. Several Dutch universities of applied sciences have started departments focused on 3D printing. They chose different target areas, such as materials, design, management; or application areas such as health, bio-plastics.
- **Increase participation** in university education by those seeking professional education.
- **Sharing information** on labour markets and curate a common, consistent image around existing and new occupations and tasks.

These actions should increase the attractiveness of technical occupations and the relevance of skills learned as well as the volume of especially professionals following education besides their jobs.

Source: http://www.brainportnetwork.nl/nl?cm=188%2C420&mf_id=404

Concluding remarks

Additive manufacturing is indeed a revolutionary production technology, of which we have seen just the advent. In the period towards 2025 and beyond we will see increased technological maturity of AM, first on a **per material basis**, then for mixed materials. This process will determine the adoption path of AM **per industry**. Eventually, AM applications are expected in **all manufacturing industries**.

In this process, the opportunities are manifold for people with **skills** related to materials, IT, data science, process engineering, process operations, product design, quality management, to name the main examples. One of the main themes for **collaboration** between industry and education institutes is adapting curricula and training programmes.

AM is mostly used in **professional, industrial settings** because of its technological complexity and the financial resources and skills needed to install, test and fully benefit from AM machines. To some extent, AM will **democratise** and localise production. However, a home production revolution is not expected. Rather we will see the emergence of small, local general purpose factories and the dissemination of AM technologies to fab-labs and maker spaces. In addition, AM can democratise production by enabling bridge manufacturing, where products can be sold already before the mass production stage is completed. This can deliver essential initial cash flow to start-ups and other small companies. As such, entry barriers are reduced and the variety of companies can increase, at least until industries enter phases of consolidation.

A counter trend was identified as well. Through the increased digitisation of production processes and value chains (including AM, robotisation and Internet of Things applications) large and IT-intensive companies connect their production processes. In these **highly-orchestrated value chains**, entry barriers can increase. A minimum efficient scale is needed to link up to the IT systems and to obtain any certifications required and meet stringent quality standards. Moreover, these highly integrated value chains could mean that one or two large companies basically dictate the processes of suppliers, clients and business partners.

In terms of value creation along the value chain, of specific interest is **product design**. We have seen that eventually AM can displace or reduce the value added of activities at the heart of the manufacturing process: 'the tasks taken over by AM machines and (other) robots'. The product design phase can become more important for competitiveness. This requires a rethinking of the (economic) appreciation of design. Manufacturing companies will have even stronger incentives to invest in talented product designers, especially is they also have the skills to collaborate with materials experts, process designers and process operators. But what would happen if we could download and materialise the blueprints for any product at a local copy-shop? The economic turmoil and disputes around Intellectual Property of designs that this may cause, could be similar to that around the introduction of peer-to-peer sharing and its impact on the music and film industry.

AM's attractiveness towards the public lies in part in the charm of **materialising objects that are digitally distributed**, which appeals to the Star-Trek like *Replicator* that rearranges sub-atomic particles into desired objects. Though we are not there yet, the introduction of a very primitive version of such technology for less than the price of a telephone is bound to spark imagination and creation, certainly by those who grow up with it. As we learned through our workshop, one of the big remaining questions, even at companies that use AM, is "what do we do with it?" This very question makes predictions about the impact of the technology other than extrapolations difficult. And exactly this is the reason that the introduction of AM at (primary) schools is advocated by several interviewees. There is a need to experiment.

The same uncertainty complicates any discussion about the impact of AM on **work**. Implications for skills needs, education and training can be addressed, linked to observations about the increased relevance of intellectual and social tasks. Discussions about working conditions can only identify possible safety risks and scenarios under which some occupations can turn into routine jobs (e.g. filling and cleaning a 3D printer) or into a job that combines a variety of tasks (e.g. a AM process operator).

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Annex A: Research questions

1. What aspect of new technologies can be considered game changing to the manufacturing industry?
2. In what area of the industry are technologies entering the manufacturing process?
3. What drivers and motives of enterprises shape the uptake of these technologies in the subsectors of the European manufacturing industry?
4. How likely is the increase and uptake of the technologies within manufacturing?
5. To what extent are the five technologies changing processes within the value chain?
6. How are these technologies affecting the demand for materials and products required within the European manufacturing industry?
7. In what way does the adaptation of the technologies impact work processes within the industry?
8. How are these impacts likely to expand and evolve in the next ten years?
9. How are the technologies changing employment, notably in terms of:
   - The need for new skills and competences
   - Increased demand in existing skills and competences
   - New occupation development
   - Increased demand of existing occupations
10. How are the (potential) changes caused by the technologies affecting working conditions in terms of job quality, contractual arrangements, health and safety and work organization?
11. How are social partners responding to and preparing responses to the changes in working conditions, occupational demands and skill needs?

Annex B: Interviews

Expert	**Organisation**
Mats Falck	Umeå University, leader of Swedish national agenda for research and innovation in Additive manufacturing, and chairman of the Swedish Association of AM manufaturers (Sveat)
Fried Vancraen	Materialise Leuven
Richard Hague	EPSRC Centre for Additive manufacturing, Faculty of Engineering
Jos van Erp	Programme Director Human Capital Agenda, Holland Hightech
Chantelle Kiernan	Scientific and Innovation Adviser in IDA Ireland
Roland Sommer	Director of the Industry 4.0 platform in Austria

Annex C: Workshop participants

Expert	Organisation
Arno Gramsma	KNWE / Addfab (manufacturing company)
Rein R. van der Mast	Fontys (university of applied science)
Peter Cox	Brainport Development (regional development)
Jan Moeskops	Techniekpact (NGO to stimulate education in technology)
Fredy Pelzer	FNV (Dutch labour union)
Joost van Barneveld	Technopolis Group
Martijn Poel	Technopolis Group