EUROPEAN COMMISSION

EXECUTIVE AGENCY FOR SMALL AND MEDIUM-SIZED ENTERPRISES

Identifying current and future application areas, existing industrial value chains and missing competences in the EU, in the area of additive manufacturing (3D-printing)

Final Report

Brussels, 15th of July, 2016

IDEA Consult, AIT, VTT, CECIMO

Project Data

Service Contract No.:	ENTR/300/PP/2013/FC-WIFO
Contract Title:	Framework Service Contract - Studies in the areas of European Competitiveness
Date of Contract Signing	23/04/2015
Contracting Authority	Executive Agency for Small and Medium-sized Enterprises ('EASME')
Delivery Partner:	**IDEA Consult**, Brussels (Belgium) *Project Leader* **VTT Technical Research Centre of Finland Ltd**, Espoo (Finland) *Core Partner* **Austrian Institute of Technology**, Vienna (Austria) *Core Partner* **CECIMO**, Brussels (Belgium) *Network Partner*
Duration of the Project	13.5 months

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This report was commissioned by EASME in the framework of the Work Programme 2014 of the EU Programme for the Competitiveness of enterprises and SMEs (COSME) and was prepared for the European Commission, Directorate General for Internal Market, Industry, Entrepreneurship and SMEs (Directorate F – Innovation and Advanced Manufacturing, Unit F3 – KETs, Digital Manufacturing & Interoperability).

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doi:10.2826/72202

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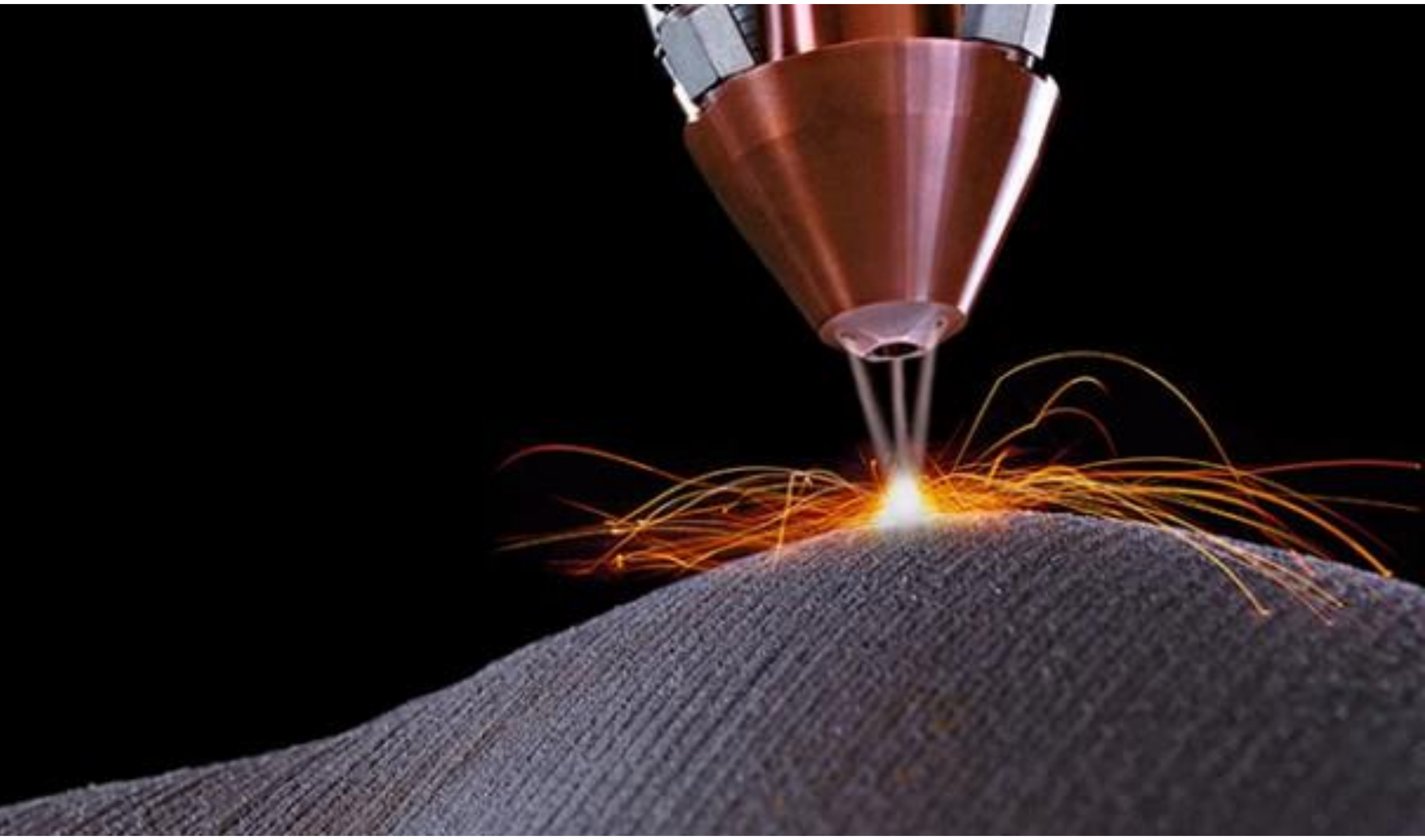


1/ Executive Summary[1]

1.1 Objectives and approach of this study

Additive Manufacturing (AM) or 3D-Printing consists in the "*process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies*"[2]. It is a technology that falls under the category of Advanced Manufacturing Technologies[3]. It is therefore part of the group of Key Enablling Technologies which are crucial for the industrial renewal of Europe. This report synthesizes the results of a study aimed at:

1) Identifying key current and emerging (including future) **application areas** in the field of AM;
2) Reconstructing the underlying **value chains** at the regional level by identifying and positioning relevant European players;
3) Identifying **missing competences** with regard to applications with a promising potential as well as **collaboration opportunities** to overcome the current and upcoming **barriers** to AM deployment in their respect.

This research was led by an international research consortium under the coordination of IDEA Consult. The research team called upon a broad range of research techniques, including:

1. A review of the literature based on the desk research
2. Quantitative analyses which covered:
    a. Patent data analysis;
    b. Analysis of FP-funded projects;
    c. Bibliometric analysis;
    d. Resulting Sectors-Applications Matrix.
3. Application-driven case studies oriented toward the analysis of 10 main Additive Manufacturing value chain which covered:
    (1) Surgical planning
    (2) Plastic-based car interior components
    (3) Metallic structural parts for airplane
    (4) Inert and hard implants
    (5) Metal AM for injection Molding
    (6) Spare parts for machines
    (7) Lighting and other home decoration products
    (8) 3D-printed textiles
    (9) Affordable houses
    (10) 3D-printed confectionery

1.2 Current and emerging AM value chains in Europe: an overview

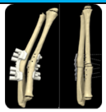
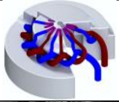
A number of AM technologies are available on the market which can call upon a broad range of materials, from powders and fused plastics to metal wires and living cells. Each of the technologies available aims at manufacturing parts and products layer by layer, a process that is usually referred to as "*printing*". Printing parts can lead to a number of technical and economic advantages that can benefit European companies in all manufacturing sectors.

The present report shows that European regions are among world-wide leaders in specific Additive Manufacturing fields such as metal AM and perform well for instance in areas related to selective laser melting or biomedical AM research. Current application areas could be identified, among which 10 were analysed from a value chain perspective. These present three main levels of maturity, ranging from the **most mature AM areas** to the **intermediary areas** and **less mature and emerging areas**. They also face strong competition from North America and South-East Asia. **Key emerging and future application areas** were also identified in the context of this project and are presented for each value chain under study in Table 1.

Overall, none of the value chains analysed in the context of this study was disrupted yet by the adoption and deployment of AM. Some first signals of **value chain contraction** (the replacement or elimination of specific value chain segments due to the deployment of AM) could however be observed, as well as the integration of **new players**. AM is however still at an early stage in most application areas (such as for the 3D-printing of food) and key developments are steered by large Original Equipment Providers (OEMs), integrators and Research and Technology Organisations (RTOs). **SMEs** are the ones facing most challenges due to their limited capabilities. Mechanisms and key features of the bargaining power of the actors involved in the 10 application-driven value chains could be identified during this study, including the role and strategies of international printer manufacturers who constitute a bottleneck along most and across value chains.

[1] CREDIT: The picture used for the cover page of the core report is issued from http://www.extremetech.com/extreme/143552-3d-printing-with-metal-the-final-frontier-of-additive-manufacturing
[2] See also http://www.astm.org/FULL_TEXT/F2792/HTML/F2792.htm
[3] See https://ec.europa.eu/growth/tools-databases/regional-innovation-monitor/link/european-task-force-advanced-manufacturing

Table 1: Emerging and future AM areas - An overview derived from the application-driven case studies

Application Area	Emerging and future AM areas per value chain
	**Surgical Planning:** Soft and flexible materials. Currently surgical planning is still mainly focused on hard tissue in the body. A large part of the body consists of soft tissue though. The materials for e.g. cardiovascular and gastrointestinal models requires elastic properties from the material. There is still a lot of potential in modelling and simulation for surgery. Very important is the identification of the problem and the quantification of the problem (diagnostic purposes). 3D-print enabled surgical planning services (induced by the availability of AM models and surgical tools/guides and the need for software and specialist service providers.
	**Plastic-based car interior components:** Printing of lightweight and/or complex parts; Composite materials for car interior component printing; Hybrid printing methods; Customized 3D-Printed cars and related business models (such as in the case of LocalMotors); Decentralised and on-site production of parts (at dealership, etc.); Printing of large components; Full production scale printing of car components; Full car printing; Multi-material and multi-color printing; Integration of components through AM.
	**Metallic structural parts for airplane:** 3D-Printing of large components and structures (aircraft wings and fuselage are current targets); Wire-based printing of metallic structural parts, which is currently at a demonstration stage; In the longer run, some see the printing of entire airplane structures as a possible (though still speculative) future area; Maintenance, Repair and Overhaul (MRO) and on-site production of (spare) parts for aircrafts; AM of small critical components and mechanically loaded parts; Use of composite materials in the printing of structural components; Development of proper monitoring and control mechanisms.
	**Inert and hard implants:** Bio-degradable material (in the next 5 years); 3D-printing of drug (in the next 5 years); Bio-printing (20 years or more).
	**Metal AM for injection molding:** AM for thermo-plastics injection molding; AM for injection molding in specific mass production sectors such as automotive (thermal exchangers, light components, and new solutions for gearbox) and packaging (bottle caps, etc.); Hybrid systems to 3D-print injection molds; Pre-series production; Prototype molds printing; Full development of digital solutions; Multi-material molds.
	**Spare parts for machines:** Maintenance, repair and overhaul (MRO); Distributed manufacturing and on-site printing of spare parts for machines (business model evolution); Non-strucural machine parts - which are not subject to guarantee issues; Spare parts for machines used in mass production sectors (automotive, packaging, etc.); On-demand (platform-based or through hubs) printing of spare parts for machines; Design selling (instead of parts).
	**Lighting and other home decoration products:** 4D printing, which will be delivering definable and varying material qualities, including electronic qualities, within one printed object, will open potential application fields for consumer products, especially for lighting products; Specific and various material qualities will be possible within one printed object, including electric conductivity.
	**3D-printed textiles:** New technologies and combination of printing materials, as well as input from other printing techniques, such as ink-jet printing, help to develop new applications thus leading to new and fast developments of 3D-printing technologies; Leight weight constructions; Smart Textiles (Electronics).
	**Affordable houses:** Printing entire buildings requires new AM solutions. One key solution offered is the use of very large printers that do either produce large pieces that can be assembled into bigger structures or come up with entire units such as rooms or houses. Another alternative and more flexible solution - the combination of robotics and AM technology - comes into play when the pieces are bigger than the printers; Online applications will appear where clients can customize their houses. New business model could appear where people can order new doors or new colors for their house even by paying monthly fees or membership money (e.g. Spotify); Temporary buildings like pavilions for festivals that only stand for a few days/weeks - or shelter in disaster areas.
	**3D-printed confectionery:** Personalised food (like adding proteins, vitamins etc) for special nutritional and dietary needs (e.g. people suffering from illnesses, elderly, health consious consumers); Substitute and alternative food materials (e.g. using insects as source of protein, 'meat' like vegan products); Emerging service innovations (e.g. new ways of serving food that create socio-technical change).

1.3 European regional AM capabilities and collaboration opportunities

Current **European capabilities** in the field of AM were mapped at the regional level in order to identify **missing capabilities** and cross-regional **collaboration opportunities**. The starting point for analyzing existing AM capabilities was to identify key players from both research and industry that are active and/or proactive when coming to adopt or develop Additive Manufacturing activities.

Leading European countries such as Germany, the UK, the Netherlands, France, Belgium, Italy, Spain and Sweden take a global lead in some specific areas, either through their position in AM systems manufacturing or through large OEMs, integrators or RTOs. Particular strengths were spotted in healthcare and powder-based technology fields. One of the **key strengths** of Europe is **metal Additive Manufacturing** (AM). Companies and RTOs are indeed proactively developing this area, making use of metal powders and wires to print molds, structural components in the aeronautic industry, but also a broad range of tools in most sectors. In other key AM areas Europe faces competition from Israel and the United States[4] (in fields such as **plastic**-based AM), Japan (in **Hybrid** Manufacturing) but also China in some emerging areas (such as **bioprinting**).

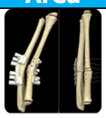
The European AM landscape however remains **fragmented** (see Box 1). The **concentration of AM capabilities** in specific **Western European regions** leaves a picture of leading regions specializing in particular segments of the AM value chain (such as Baden-Wurttemberg in the field of AM printer manufacturing for instance). Such specialization pattern can cover both supply and demand sides[5]. **Eastern (and to some extent Southern) Europe** is however at a discovery stage: only a limited number of 3D-printer manufacturers and specialized service providers could be identified in Eastern European regions. In these regions, most efforts are being made in key RTOs where public investments contributes to the absorption and development of AM knowledge and technologies.

Box 1: Fragmentation of AM capabilities in Europe – a Regional Overview

Large German Landers (Bavaria, Baden-Wurttemberg but also North Rhine-Westphalia) concentrate most AM capabilities. They are followed by French regions (such as Ile-de-France and Rhône-Alpes), the United Kingdom, the Netherlands (South Netherlands), Belgium (Flanders, Wallonia), Spain (Asturias, Cataluña). Also Northern Italy (Piemonte, Lombardy, Emilia-Romagna) and Northern Europe (the Netherlands, Sweden but also Finland and to a more limited extent Norway) as well as Austria (Upper Austria) are strongly developing in specific AM areas. Although Poland is more advanced, countries such as Slovenia, Croatia, Slovakia, and the Czech Republic are only starting to develop capabilities in the research sector.

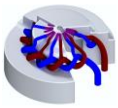
The fragmentation of the European AM landscape can be closely associated to established or sometimes emerging specialisation patterns. It also highlights the missing links between Western European regions where most AM capabilities are concentrated and Eastern European regions. **Collaboration opportunities** were therefore identified in the 10 value chains under the scope of this study, ranging from **cross-value chain collaboration** opportunities to **collaboration opportunities across the segments of a same value chain** (see Table 2).

Table 2: Overview of the main collaboration opportunities identified for the 10 application-driven value chains

Application Area	Collaboration opportunities
	**Surgical Planning:** Multidisciplinary collaboration is needed. Communication, collaboration, exchange of experiences between the different actors (material providers, service providers and users - surgeons and hospitals) is key. The same goes for universities and businesses. Especially at the level of materials, the very detailed and focused approach of material research is indicated as useful for the companies to further develop applications in healthcare.
	**Plastic-based car interior components:** Collaboration platforms already exist between the automotive and aerospace sectors; as for the other collaboration opportunities in the sector, these are by nature European (and international/global). They are mainly to take place between OEMs, AM service and printer providers, RTOs and integrators. Collaboration opportunities also exist between the car interior component value chain and other transport-related value chains in Europe. These could be concretized by dedicated collaborative projects/platforms/networks (EU scale); Other collaboration opportunities could be spotted such as between the car interior value chain and the textile value chain (through upholstery). International collaboration could take place between research centers and OEMs on this topic. Collaborations with other value chains could also take place on the basis of either the materials or systems mobilised by the sector (plastics, composites, powder bed systems).

[4] Including those with corporate offices in countries like Israel

[5] For example, not only do German Länders benefit from a concentration of metal printer manufacturers, they also benefit from the presence of large RTOs and OEMs in sectors such as aerospace and automotive that can create a critical level of demand for metal printers.

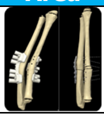
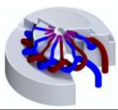
	**Metallic structural parts for airplane:** Collaborations could take place across value chains on the topic of large metallic structural parts, and mainly between the aeronautic, automotive, defense and space value chains. Such collaborations could be organized at the EU level and link key OEMs and integrators but also 3DP service and printer providers active in those value chains across regions and along the value chain. Collaboration opportunities are also found in the areas of smaller structural (and non-critical) components across the aforementioned value chains, these could take place at the EU level and involve similar players. Platforms, networks, projects and other collaborative settings would be appropriate to foster such collaboration as is already being done under H2020; Collaborations across regions could take place in this area but also making the link between this value chain and other value chains (such as in the transportation and Energy fields where common constraints apply) by connecting demonstration and testing facilities across regions. This could be done bottom-up with the coordination support from the EU level. Collaborations could finally take place around titanium-based applications which are in use in the aforementioned value chains (common AM parts were already identified that can be found in both aeronautics and space systems).
	**Inert and hard implants:** Multidisciplinary collaboration is needed. Communication, collaboration, exchange of experiences between the different actors (material providers, service providers and users - surgeons and hospitals) is key. The same goes for universities and businesses. Especially at the level of materials, the very detailed and focused approach of material research is indicated as useful for the companies to further develop applications.
	**Metal AM for injection molding:** Collaboration opportunities exist between OEMs, integrators and mold-makers but also research centers in all value chains making use of injection molding. Such opportunities can concretize at all levels (along the value chain and locally between mold makers and RTOs or AM expert companies, cross-regionally between mold makers and OEMs, etc.); Particular collaboration opportunities could be taken advantage of cross-regionally in the areas of car manufacturing and packaging (where AM molds could play an important leverage effect).
	**Spare parts for machines:** Collaboration opportunities are spotted between the machinery (incl. Equipment manufacturing) and mass production sectors (automotive, packaging, etc.); Collaborations have to be developed around the combination of subtractive and additive technologies, most likely in a cross-regional fashion, and should involve both science and industry.
	**Lighting and other home decoration products:** Regarding the relatively high involvement of European users (see e.g. Fab Labs or 3D Hubs) within 3D-printing platforms, specific opportunities for Europe could be supported financially and with specific actions, e.g. establishing initiatives such as Fab Labs, especially in Eastern European countries. Potential key regions with high concentrations of involved end users and vendors of 3D-printed home decoration products were identified (e.g. Netherlands/Nordrhein-Westfalen, in Italy, South France, and in Spain). Networking activities, knowledge exchange platforms, and other actions could support local players and raise common awareness.
	**3D-printed textiles:** Especially collaborations between research institutes and textile industry (including between designers and OEMs), and also with 3D-printing end users, including 3D-printing communities. Opportunities emerge in suing textiles in other industries such as automotive and aircrafts (Cross-sectoral collaboration). Collaborations should be supported, especially between research institutes and textile industry. Collaborations with companies from Eastern Europe where many textile manufacturers are located (although they are often subsidiaries from MNE).
	**Affordable houses:** Collaboration between various value chains e.g. construction sector with aerospace industry and defense industry both on national and European level. More collaboration is needed between different fields. Especially cooperation between architects and experts from robotics, software and construction industries is needed.
	**3D-printed confectionery:** Fostering of research collaboration at European level by including private unprejudiced innovative food technology companies into projects, and improving knowledge exchange of European research organisations in common projects. Sharing of facilities and platforms of 3D food printing at the current exploratory phase should be encouraged at the regional level. Encourage research partners to adapt open innovation and co-creation principles. This would also potentially lead to the development of stronger regional ecosystems linking research organisations and the food industry. The research of 3D printing in food would benefit of European level research projects that integrate technology and business development. Understanding from food processing technologies, business models and consumer acceptance are to be strengthened simultaneously.

Collaborations can take place between specific actors acting in a same (regional) **ecosystem** as one can observe in the field of AM for injection molding; or across European value chain segments (whether across or along value chains) such as observed in the context of the **collaborative** projects and platforms linking the automotive and aerospace AM value chains. Depending on their format, collaborations can involve 3D-printer manufacturers, services providers and OEMs or integrators. They can also involve RTOs players when a need to address particular technological issues is identified. **The levels of both specialisation and fragmentation of AM in Europe particularly calls for international and cross-regional collaboration**. Collaboration opportunities (each being value chain-specific) can or could link Western and Eastern European regions, supply and demand, in an open innovation fashion.

1.4 Missing capabilities and barriers to the adoption and deployment of AM in Europe

The fragmentation of the European AM landscape is also to be considered at the light of **under-developped and missing capabilities** which were identified in the course of this study. These are presented in Table 3 and consist in value chain segments (or related functions) that could be strengthened in Europe. They mainly translate in the absence or lack of key players. In the field of metal AM for aeronautic components for instance, Europe is missing companies able to produce high-end metal powders for specific applications. In a less mature field such as food printing, Europe is missing specialized companies able to take existing technologies and materials to another level.

Table 3: An overview of missing and under-developed capabilities per value chain under study

Application Area	Under-developped and missing capabilities
	**Surgical planning:** Materials capabilities (not only hard materials but also soft tissues, etc.); Capabilities are mainly concentrated in Western European regions; The software segment should further be developed.
	**Plastic-based car interior components:** The CAD software segment could be strengthened further; Capabilities are mainly (if not exclusively) concentrated in Western European regions.
	**Metallic structural parts for airplane:** Transformative capabilities to turn high-end materials such as titanium and alluminum into powders are missing in Europe; CAD capabilities should be further developed; Non-Destructive Testing (NDT) and broader testing capabilities; Post-processing (including finishing) capabilities should be further strengthened; Capabilities are concentrated in Western European regions; Wire-based AM systems and appropriate software capabilities are currently missing in Europe; Hot Isostatic Pressing (HIP).
	**Inert and hard implants:** Capabilities are mainly concentrated in Western European regions; Software (incl. simulation/modeling) capabilities should be further strengthened in the sense of customisation.
	**Metal AM for injection Molding:** Transformative capabilities in high-end powders; AM Supply capabilities are mainly concentrated in Western European regions and the users are part of a scattered landscape; Software capabilities could be further strengthened to face international competition.
	**Spare parts for machines:** All the value chain is currently at an early stage of development: no clear supply chain could be identified beyond specific (and/or isolated) cases; However, finishing and post-processing capabilities remain to be developed (surface finition is key to this application area).
	**Lighting and other home decoration products:** Although they are to develop, no particular capability appeared to be missing in this value chain – existing capabilities however remain to be bundled.
	**3D-printed textiles:** Software and simulation capabilities can be further developed; Adapted systems (in view of in-line production), incl. relevant interfaces; The landscape remains scattered; New (elastomeric, rigid, conductive, etc.) materials.

	**Affordable houses:** Overall the 3DP activities related to affordable housing are scattered over Europe with only few countries and some of their regions that do well such as the Netherlands and the UK. To reach critical mass it would be beneficial to bundle forces. Eastern-Europe seems not to have activities in this field apart from some SMEs activities from Slovenia. A majority of the most important activities seem to be concentrated in Western Europe (German speaking regions for material development and robotics, UK and the Netherlands). One additional missing capability is not technological but relates to the financing and ownership strategies of promising ventures especially in the fields of design and software development. It seems that the continuity of European ownership is not always realized in this field what may potentially hamper optimal growth of the company targets and their European ecosystems. Furthermore even and especially in countries that are active in the field there seems to be a need for 'bridging people' that understand robotics, software and the construction sector as to make development projects more successful.
	**3D-printed confectionery:** Because of the scattered and small number of actors, one of the main missing capability in the 3D-printed food in Europe is the lack of specialization; The food industry is not only waiting good results from pilot production examples, but the machines and raw materials for industrial use are missing as well; The main activities in the 3D-printing in food are concentrated on few Western European countries, and no clear indication of companies or research actors from Eastern Europe that have engaged in 3D-printed food is available.

It is also important to highlight that some of the missing capabilities can even stand as a critical barrier to the deployment of AM. There relate to missing knowledge or key players in a specific area. Two main missing segments where no or few European players are active are in that respect:

- High-end metal-based material capabilities (and in particular **transformative capabilities** of materials such as titanium, aluminum and magnesium – see Box 2);
- And the post-processing segment (where Hot Isostatic Pressing is absent and finishing as a whole is to be developed).

Box 2: Eye On the Issue of Metal Powders – The focus on transformative capabilities

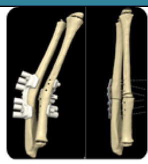
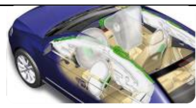
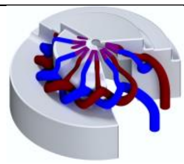
It has been acknowledged that AM materials require further development[6]. The present report mainly highlighted the critical importance of **aluminum**, **titanium** and to some extent **magnesium** to the European AM industry. Among the three types of materials, only magnesium (which is also used in almost all aluminum alloys) was considered a critical material in 2010 and in 2014 as 96% of the supply came from the 20 most significant producing countries and 86% from China[7]. While there is in addition "*no significant production [of] (…) titanium in within the EU*"[8,9, 10], Europe is an aluminum producer[11] and a leader in aluminum recycling[12]. The titanium industry is concentrated in both supply and demand markets, pursuing its vertical integration. Aluminum on the other hand is subject to a low level of concentration. Metals such as aluminum and titanium in particular are concerned with both **technical** and **economic difficulties**, and **processing** appears to be a main challenge[13]: skills, knowledge and modeling are areas that require further support in that respect. One can notice that AM is not among the largest consumers of metal powders. These are however **critical to the AM industry**. The present report shows that besides raw material supply, **transformative capabilities are the ones to be further developed in Europe**. These consist in activities aiming to (and related organisations able to) transform and recycle (raw) materials into proper AM materials (such as powders, wires, etc.). This segment was found as being a key missing/under-developed capability.

In addition to the analyses of current AM capabilities, key **barriers** were identified for each of the 10 selected application areas and underlying value chains. These barriers hamper or even block the **adoption** and **deployment** of Additive Manufacturing. Many of these obstacles are recurrent and can be found in most of the value chains under the scope.

[6] Measurement Science Roadmap for Metal-Based additive manufacturing. National Institute Standards and Technology, US Department of Commerce. 2013. http://www.nist.gov/el/isd/upload/NISTAdd_Mfg_Report_FINAL-2.pdf
[7] Source: http://www.polinares.eu/docs/d2-1/polinares_wp2_chapter2.pdf
[8] Source: http://ec.europa.eu/DocsRoom/documents/10010/attachments/1/translations/en/renditions/native
[9] In Europe, only Norway produces titanium (See http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical/index_en.htm).
[10] See http://titanium.scholarlab.com/customer/titanium/resources/tieurope2014/SchneiderUweWorldIndustryDemandTrendsTiEU2014.pdf
[11] https://ec.europa.eu/growth/tools-databases/eip-raw-materials/sites/rawmaterials/files/Bauxite%20-alumina%20-aluminium%20Presentation%20.pdf
[12] See http://ec.europa.eu/growth/tools-databases/newsroom/cf/itemdetail.cfm?item_type=251&lang=en&item_id=7054
[13] Source: https://ec.europa.eu/research/industrial_technologies/pdf/metallurgy-made-in-and-for-europe_en.pdf. Pg.46.

The lack of **knowledge** is among the most recurrent ones and mainly consists in the lack of skills and appropriate curricula, but also in the lack of knowledge available to characterize and standardize the AM materials and processes at stake. The **technical** limitations but also the **cost** of AM (materials, printers, etc.) and the lack of **awareness** among potential user communities are also recurrent. They come together with difficulties to overcome traditional ways of manufacturing and **cultural** barriers in private sector organisations. Barriers to the uptake and deployment of AM along the selected value chains are also strongly linked to the structure of the market and composition of the chain (including underlying mechanisms such as the bargaining power of users). An overview of the barriers referred to for each of the studied value chains is presented in Table 4. Most of these barriers highlight the **need for improved demonstration** in Europe. Many of the needs that are indeed identified relate to higher Technology Readiness Levels (TRL)[14] and to needs that are proper to close-to-market barriers (such as the need to relate to customers and the demand side, the need for efficient processes, the lack of information and other business and market-related factors, etc.).

Table 4: Overview of the main barriers hampering AM uptake and deployment in 10 application-driven value chains

Case Study	
Surgical Planning: lack of training and appropriate skills (CAD, management, manufacturing, etc.); the lack of a multi-disciplinary approach; the lack of awareness across the user community; the fact that printers remain expensive and not precise enough; the rise of virtual reality technologies allowing for virtual planning and therefore competing with AM-based surgical planning.	
Plastic-based car interior components: limited performance of AM regarding efficiency, surface quality, automation, scale economies and the printing of large parts; the fact that 3D-printed parts remain expensive and not fully sustainable but also that post-processing is still needed; the lack of qualification of AM materials and processes as well as appropriate design rules; the lack of appropriate curricula and skilled workforce; the risk-aversion and manufacuting conservatism of company and technology managers; design/CAD IPR.	
Metallic structural parts for airplane: rising competition from composite materials; heavy regulations; lengthy development plans; the lack of knowledge and skills; printer manufacturers' strategies regarding powder uses (use of specific powders made conditional to the use of certain printersà; the need for common standards and further characterization of AM materials and processes; missing knowledge (about health and security implications of AM); scalability issues; poor quality and surface finishing; the lack of detection, monitoring and control of surfaces; the lack of transformation capabilities in Europe and the availability of high-class, passivated clean powders, including aluminum, magnesium and titanium; the lack of streamlined information and insufficient awareness.	
Inert and hard implants: this area is constrained by users' low adoption level; certification requirements and related uncertainties; IPR and regulation concerns; technical isssues; the quality and availability of relevant materials; the current regulatory framework; limited skills and technology development (including R&D/characterisation and standards).	
Metal AM for injection molding: printers and powders remain expensive (mainly for SMEs) but also faces issues such as: skills availability; growing demand toward AM system manufacturers; cultural conservatism; lack of AM awareness; lack of demonstration activities; lack of multi-disciplinary curricula; AM technical limitations (cleaning of cooling channels, printing of large molds, precision and surface finishing, etc.); insufficient qualification and certification of AM materials and processes; transformative capabilities in the field of metal powders; players standing as bottlenecks in the field of metal powders[15]; fear of having companies' designs stolen; development of internal AM capabilities in client companies; little bargaining power of SMEs; international competition coming from plastics and composite materials; design/CAD IPR.	
Spare parts for machines: AM is expensive and sub-optimal; appropriate skills and curricula; risk-avoiding culture; availability of spares; need for a clear available distributed network; designs availability; printers' warranty and replicability of the parts; missing knowledge about AM materials and processes;; differences between materials, printing conditions; lack of precision of AM.	
Lighting and other home decoration products: technical limitations (production time, finishing, quality, toxicity, stress testing, costs); need to develop materials and processes (incl. 4D-Printing); the market is small and dedicated to expensive designer products; only few key players are active in this area; missing knowledge about 3D-printing; consumption is low; awareness and quality information are missing.	

[14] See http://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

[15] e.g a printer manufacturer conditioning the use of its printers to the use of its powders.

3D-printed textiles: lack of technological knowledge; missing fast in-line processes; insufficient mechanical properties; inadapted textile CAD data; insufficient resolution; need for process and materials characterisation; need for simulation and software; AM productivity; lack of common research and interactions between key players; concentration of supply capabilities in Western Europe; limited performance (size of the product, printing length, costs; missing material (from elastomeric materials to rigid or conductive materials) and finishing capabilities; lack of new business models; strength and quality of materials.	
Affordable houses: limitations of current robotics and printers; no part integration, multiperformative and multimode operations; need for computerized assembly lines; size, volume and cost of AM; complexity of human/robot interactions; materials; scale; speed; skills; current paradigms; conservative and risk-avoiding culture; lack of multi-disciplinarity; lack of awareness; standardization, building and safety regulations; lack of creative entrepreneurship[16].	
3D-printed confectionery: Heat and ingredients; AM performance; missing knowledge; lack of critical mass; knowledge about temperatures during the extrusion process; consumption habits; image of AM food; price of AM food; food safety; absence of regulations; lack of viable business models; not all food ingredients are applicable to 3D printing yet; need for technologies to extrude multiple ingredients.	

1.5 Policy implications

Policy implications were derived for each of the cases which are presented in more details in Section 4 of the Background Report. These can be synthesized under the following headings:

Acting at the level of Human Resources

1. **Skills** and the availability of appropriate and **multi-disciplinary[17] curricula** are a crucial issue to be addressed. This was identified as a key barrier to be overcome in all case studies. Training should be made available which would deal with AM and particular aspects of AM (such as CAD, materials, management, etc.). Such development is most likely to take place at the level of EU Member States, but the European Union could take a coordination role in order to streamline efforts made in this area.
    - A consultative process could for instance be launched by the European Commission which would trigger collaborations between education stakeholders and the AM community. This participatory process could gather relevant stakeholders and key organisations to shape up a new ground for multi-disciplinary curricula at all education levels and how to ensure their uptake.
2. **Awareness** should be raised at all downstream levels of the value chains under the scope: engineers, technicians, R&D and company managers, but also consumers and end-users in general should be made aware of the pros and cons of AM in order to allow for the necessary cultural shift. The so-called cultural shift both concerns the focus on formative and subtractive methods as well as the reluctance to adopt new – less proved – technologies.
    - Two main tools could be mobilized in that respect: first, the European Commission could initate a one-stop shop that could take the form of a website dedicated to Additive Manufacturing and of which content could deal with the various aspects of AM in Europe but also world-wide (incl. links to calls for projects, an interactive mapping of key AM infrastructures and services, etc.). A second tool would be thematic events to target 1) (potential) users and 2) company managers. These events would be oriented toward particular issues that are key to the competitiveness of particular value chains or application areas.

Acting at the level of the technology

3. **R&D support** (including experiments and prototyping) is required in all areas, whether emerging or already advanced. Technical barriers related to the size of the printed parts, the efficiency of the process, etc. are key barriers to be overcome in order to make sure AM reach an appropriate level of maturity in the areas where Europe has or can develop a comparative advantage. R&D support is most likely to be collaborative in order to allow for knowledge and technological transfers and broader diffusion. By collaborative, it is meant that R&D should bring together RTOs, large companies and SMEs, as well as users[18]. Such support could be brought at the regional, national and European government levels.

[16] A lack of focus from entrepreneurs on issues such as culture and design, IT and gaming, infrastructure, safety thinking (related to housing issues), standardization, sustainability.

[17] When taking the example of affordable housing, such multi-disciplinarity could involve mixing robotics, software and construction, with particular emphasis on design and software development. In the food sector, these would entail food sciences, processing technologies, etc.

[18] And to the extent relevant government authorities.

Box 3: Examples of R&D areas to be supported

- **Surgical Planning**
  - Research on materials: (a) on elastomeric type of materials which can be used for medical models and (b) multimaterial printing;
  - Research on the accuracy and the fidelity of the 3D-printed models;
  - Design features for 3D-printing[19].
- **Plastic-based car interior components**
  - Quality, consistency of production outputs;
  - Composite materials for car interior component printing;
  - Application of biomimicry to the AM of car components.
- **Metallic structural parts for airplane**
  - Explosivity of metallic nano-sized powders;
  - Quality of material feedstocks in powder-bed AM systems;
  - Properties of large multi-material and composite-printed structural parts for airplanes.
- **Inert and hard implants**
  - Research on materials: the strenght and porosity of the inert and hard implants (towards the future: futher research on biodegradeble materials and bio-printing);
  - Design features for 3D-printing[20];
  - Userfriendliness of the user features of 3D-printers. Often there is no automation or only semi-automation.
- **Metal AM for injection molding**
  - Bi-material (copper and steel) mold printing;
  - Hybrid printing and the finishing of cooling channels in injection molding;
  - Inter-operability of metal powders such as titanium and aluminum powders.
- **Spare parts for machines**
  - Post-processing and the finishing of surfaces with mechanical properties;
  - Hybrid manufacturing (combining additive and subtractive techniques) of (non-) structural components for machines such as air compressors, compellers, water pumps, separators and parts of forging machines;
  - Analysis of distribution patterns of spare parts for the development of additive/subtractive hubs.
- **Lighting and other home decoration products**
  - AM processes; Printing qualities are still not sufficient for small objects and products often need further surface treatments after printing;
  - Material properties; Technological advancements, e.g. 4D printing, which will be delivering definable and varying material qualities, including electronic qualities, within one printed object, will open potential application fields for consumer products, especially for lighting products;
  - Toxicity, explosivity and broader health impacts of used materials.
- **3D-printed textiles**
  - Quality monitoring, control and detection systems;
  - Recycling and sustainability are the strongest arguments for 3D-printing as production can be achieved without too many remnants and waste;
  - Materials selection, materials properties including health impacts (esp. also recycled materials, such as cellulose fibres).
- **Affordable houses**
  - Materials should still be developed that can be processed on printers or contour crafting machines and that can fit the requirement of the building industry;
  - How AM, robotics and automation together can change the way things are done in the construction sector[21];
  - Software development.
- **3D-printed confectionery**
  - Technologies of 3D food printers (e.g. temperature fluctuations during extrusion process, printing speed);
  - Creating of multi-textural food structures (e.g. printing of different layers with materials that have different viscosinity);
  - Research in viscosity and consistency of food materials (e.g. particle size of printanble materials).

[19] Currently the design process of 3D-printed implants is very long and complex. There is certainly a need for further improvement of the medical imagine-processing software. The "connection" between CT-data and intelligent design of applications can still be improved.

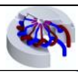
[20] Currently the design process of 3D-printed implants is very long and complex. There is certainly a need for further improvement of the medical imagine-processing software. The "connection" between CT-data and intelligent design of applications can still be improved

[21] The assumption is that the industry is not only going to use 3D-printing but a whole set of different operations into the building process. In the factory of the future, they see the building process completely robotized. Alternatively robotics could be included in the 3DP category or appear as another value chain with which collaboration has started

- R&D support would most likely be collaborative and applied cross-regionally. A broad range of instruments could be mobilized in that respect: networks of infrastructures connected across European regions and coordinated at the regional level; collaborative R&D projects supported by regional, national and European authorities; as well as other targeted tools such as innovation vouchers or financial incentives (R&D tax credits at the national level, etc.).

4. Among the key areas to be supported, the **combination of subtractive and additive methods** (for instance in the form of hybrid manufacturing) is to be supported in order to make Europe able to compete with Japanese competitors on a high-potential segment.
5. Europe is well-placed to **streamline all standardization and certification efforts** being made in the context of different value chains. The inter-operability of materials is for instance a key area where public support would benefit the industry. It is however important to note that standardization is only useful when the technology is characterized and mature enough. Examples of possible working areas relevant to standardization efforts are provided in Box 4, showing that qualification is to remain a priority in some of the application areas under the scope.

Box 4: Working areas to guide standardisation - Examples

Area	Description of the working area	Status
	Standards on classifying and labelling 3D printed food are needed. 3D printed food safety regulation, mainly in serving and distributing food (e.g. hygiene of self serviced 3D printers and vending machines at supermarket, producing food vs selling packaged food) is also a key area.	*Standardisaton working areas*
	Standards should be found in the field of plastics used as material for car interior components and which should present certain mechanical properties.	
	Powders inter-operability in order to ensure the operational functioning of powders in powder-based systems.	
	Metallic powders should be subject to further characterisation before being subject to standardisation. Standards should be developped for powder-based systems but are also needed for wire-based processes to spread.	*Characterisation and standardization running in parallel for different systems*
	Several materials used for 3DP are currently being investigated and their properties are actually not known yet, meaning that standardisation can only happen at a later stage. Qualification will therefore matter in that respect.	*Qualification and certification as main priorities*
	Regulatory framework: uncertainty with respect to certification at national and EU-level hampers the uptake of AM. A clear regulation with respect to certification should be developed.	

6. European **Fab Labs** (Digital Fabrication Laboratories) should be **used as test beds**[22]. Regions would be well-placed to steer such tests due to territorial proximity.
7. Another example of policy implication relates to Intellectual Property Rights (IPR). The current analyses suggest that monitoring and enforcement could reduce the risk-avoiding behaviour of most companies active in different markets and who could take advantage of AM depending on the area (see Box 5). Examples of actions are listed below, which are illustrative only (further analysis is recommended to assess the need and usefulness of the listed examples):
   - Information capabilities of key Intellectual Property instances could for example be strengthened by setting up an observatory (which could be related to the EPO and/or IPO for instance)[23] in order to watch over new industrial designs and their reproduction.
   - IPR regimes could be enforced at both EU and national levels. This particularly concerns the protection of design patents and copyrights over original parts.
   - Monitoring acquisitions in the field of construction AM would allow following where the most important IPR portfolios are and monitor new market dynamics.
   - Meaningful IPR could be boosted by bundling resources for top European research.
   - In the field of consumer products, IPR helpdesks and IPR support from the public could also cover new forms of IPR such as creative commons, rules concerning open source software development, etc.

[22] This is applicable to all value chains, with a particular interest from the side of food printing and textiles.
[23] Examples are provided in http://www.tandfonline.com/doi/abs/10.5437/08956308X5705256 and on http://ubiquity.acm.org/article.cfm?id=1008537

- In sectors such as mold-making and textiles, activities supporting the involvement of users could have an open source character. Collaborative contracts with RTOs should in any case be made clear and SMEs could be supported, protected, and informed about the possible options available to protect their designs.
- Collaborations could be foreseen in order to capitalise on upcoming working groups and current progress in the definition of AM-related IPR lines[24].

Box 5: The importance of IPR - Addressing current and anticipating on future issues

Although IPR were identified as current barriers to the adoption[25] of AM in the mold-making and automotive sectors, they are not perceived as main barriers to the deployment of AM in the aerospace, surgical planning and spare parts cases[26]. In the first two cases, the key IPR issues relate to AM designs and copyrights. Industry players fear that their designs could be stolen and that their parts/tools could be reproduced. In addition to those two groups, 3D-printed hard and inert implants, confectionery, affordable houses, home decoration products and textiles are areas where IPR issues could arise in the future but such development is to be approached carefully. Policy implications were therefore suggested in line with the different levels of maturity and related importance of IPR issues.

Developing missing or under-developed AM capabilities

8. As already pointed in the case studies, the access to high-end materials is crucial. Europe is subject to missing capabilities in this area. Therefore, European and National but also regional entities should facilitate the **access to critical materials[27]** (titanium, aluminum, magnesium, etc.) and more precisely develop the related **transformative capabilities** by supporting initiatives such as:
   - Market intelligence;
   - Improvement of business development conditions;
   - Capacity development through co-investment (in transformative processes for instance) that could take the form of direct R&D support or financial incentives;
   - Support to the qualification and standardisation of the materials through strengthened coordination at the European level;
   - Urban mining[28] to be developed at the local level with the support of higher levels of government.
9. Other capabilities should be further strengthened, for instance using similar tools than the ones referred to in the context of supporting metal powders transformative capabilities:
   - Some functional capabilities are still missing in Europe that are crucial to the further deployment of AM. These mainly concern **finishing** and in particular **Hot Isostatic Pressing** in the field of metal AM.
   - Other capabilities should be developed or reinforced at the level of the first segments of the AM value chain. These include 1) **simulation** and 2) **testing**.
10. The development of **new business models** should be supported: new business models are indeed required in areas such as food printing but also in automotive where companies such as LocalMotors in the US already introduced a new form of car manufacturing to the market. This is also the case for the textile value chains where user-driven **platform-based models** are to be further explored.
   - Digital policy should therefore foster intelligence in the field and facilitate the testing of new business models (at both European and national levels).

Bringing AM applications closer to the market

11. Closer to the market, **pilot production and demonstration capabilities** is to be further supported and connected across European regions. **Cross-regional demonstration activities** should be supported as well as **joint actions** and collaborations among exising actors, whether on a case-by-case basis or through (a) one-stop-shop(s). This would allow a better connection between supply and demand as well as to flow knowledge and network within the EU, and in particular towards Eastern European regions.

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[24] See for instance https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/421543/A_Legal_and_Empirical_Study_into_the_Intellectual_Property_Implications_of_3D_Printing_-_Exec_Summary_-_Web.pdf as well as https://www.gov.uk/government/publications/3d-printing-research-reports.

[25] IPR are a key issue in all value chains under the scope. They were however not identified as key current barriers to the adoption and/or deployment of AM. In most value chains, the weight of IPR as a policy issue is expected to grow, but it is recommended not to design and implement policy in a premature fashion.

[26] In the field of spare parts AM, the issue rather relates to the general terms and conditions that are contract-based and lead to conditions over the warranty associated to one or another machine.

[27] Through certain initiatives such as studies and projects, the EC contributes to this ambition. One can for instance refer to the study on the legal framework for permitting, Horizon 2020 project MIN-GUIDE developing a European Guide to Minerals Policy, Horizon 2020 project MINATURA2020 developing a concept of Mineral Deposit of Public Importance to secure access to deposits. A part of Horizon 2020 will also most likely contribute to put in place appropriate framework conditions, social aspects and industry competitiveness, as well as appropriate policy settings. Among others, the EC collaborates with the European Institute for Innovation and Technology (KIC on Raw Materials) on setting up a European Investment Platform on Raw Materials and Recycling in the framework of the European Fund for Strategic Investments.

[28] 'The process of reclaiming compounds and elements from products, buildings and waste.

- The European Commission could take an orchestration role in that respect, by supporting the setting up of relevant networks, structures and upgrading of current/emerging capabilities. In particular, it is of utmost importance to develop appropriate funding mechanisms for cross-regional demonstration activities. Such a funding mechanism should target in priority 'post-prototyping activities' and upscaling activities; it shoud also go far beyond the support of single projects. There is a need to set up permanent (networks of) demonstrators as joint-demonstration platforms, to become the basic infrastructure for a pipeline of industrial demonstration projects.

12. **Collaboration is to be fostered** (see examples in Figure 27).
    - Collaborations could be triggered on the basis of similar technical concerns (the use of particular systems and/or materials, the manufacturing of particular parts of products, etc.) shared by key actors from different value chain segments.
    - While **existing** collaborations (between automotive and aeronautic players for instance) can be supported, the **emergence** of others also requires public intervention (such as in the case of injection molding where collaboration between RTOs and mold-makers is to be facilitated). A wa to trigger such collaborations would be collaborative R&D support but also cluster initiatives that could be supported by national and regional entities in collaboration with the European Commission.
        i. **Cross-value chain fertilisation** would allow speeding up the market deployment of AM across value chains. There is a clear opportunity for European authorities to take advantage of existing (nascent) collaborations and foster the emergence of new collaborations across value chains[29] on common AM issues.
        ii. Not only collaboration can take place across value chains, but also **along relevant value chains** by fostering collaborations between segments such as presented in Table 34 which provides selected examples of possible collaboration opportunities both across and along value chains.

Stimulate and orient the demand side

13. Whether emanating from users or consumers, demand is key to most AM value chains under the scope. There is an **opportunity to stimulate demand** in an appropriate way across the value chains under the scope.
    - *This could for instance go through integrators in the automotive market, the consumers in the* food market, etc. Affecting food preferences or using regulation could impact the growth of AM deployment in many value chains.
14. Demand could be activated in different ways depending on whether the demand is rather baded on Business-to-Business (B2B) or Business-to-Consumer (B2C) mechanisms:
    - From a B2B perspective, two possibilities arise:
        iii. The price of AM is a recurring issue that keeps SMEs with limited capabilities but also larger risk-avoiding **companies** from investing in 3D-Printers or AM services. **Co-investment** is therefore needed from public authorities in order to facilitate the **testing** and the **acquisition** of printers. Innovation vouchers could for instance be used to facilitate the access of SMEs to relevant Research and Technology Organisations (RTOs). Tax (credit) schemes or other financial incentives could also be mobilized in that respect.
        iv. Another aspect is based on the findings from the aeronautic value chain under the scope. It is showed in this case study that environmental regulation can affect airlines, which put pressure on integrators and OEMs so that they design and manufacture optimized airplanes with reduced levels of CO2 emission. Similar mechanisms could be applied to a broad range of application areas as to foster the deployment of AM.
    - From a B2C perspective, **user platforms should also be financially supported**, especially in the benefit of Eastern European regions so **that** Fab Labs can emerge across Europe. Platforms and networks for consumer participation could for instance be strengthened in fields where consumers play a key role such as in wearables, homen decoration but also confectionery.
15. In all fields a need for a **common repository**, **streamlined information and awareness raising** was **flagged**. This could be operated at the European level in order to make sure that a homogenous set of information is managed and diffused, not to be confused with marketing by potential user communities who would be the main target.
    - An example could be to have a one-stop website (serving as repository of information) sponsored by the European Commission and managed in collaboration with research and industrial communities such as suggested under the first heading of policy implications (Point 2). Such website could among other things aim at clarifying the European AM landscape, make clear the pros and cons of AM, and stand as a gate for organisations willing to collaborate on specific AM developments.

[29] For instance between defense, automotive, space, aeronautics, transports; but also between textiles and a number of other value chains; etc.

16. Current national and European regulation and policies are to be streamlined in order to clarify the extent to which **regulation** will be adapted as to scale-up living lab experiments into real commercial products.

Box 6: From AM applications and value chain analyses to policy analysis

This study developed knowledge about European Additive Manufacturing value chains. It depicted to some extent key areas of action to support the adoption and deployment of Additive Manufacturing as well as the structuration of 3D-Printing value chains in Europe. Dedicated research would however be needed to assess the potential effectiveness of specific policy tools and instruments to address the key needs, barriers, challenges and opportunities identified in this report. Such study could develop an analytical framework to study the effects of specific policy instruments over the process of additive manufacturing deployment.

2/ Context and background of this study

2.1 A European policy framework to support industrial renewal

The European Commission recognises the central importance of industry for **creating jobs and growth**, being the backbone of the European economy, accounting for 80% of Europe's exports, for 80% of private research and innovation (R&I) and providing high-skilled jobs for citizens. However, the recent economic crisis has led to the loss of some 3.5 million jobs since 2008 and a further decline in manufacturing to 15% of GDP, far behind from the 20% target of industry's share by 2020, as per the Communication on *"An integrated industrial policy for the globalisation era"*, a flagship initiative of the **Europe 2020 strategy**[30]. Urgent reindustrialisation and modernisation of the European economy are therefore necessary to create new jobs.

The European Commission has been allocating considerable financial resources to the development of the European Industry. This is particularly the case when considering research, technology development and innovation (RTDI) support. The commission brought funded RTDI since the first Framework Programme (FP1, 1984-1987) up to "*Horizon 2020*" (**H2020**), the biggest EU Research and Innovation programme ever funded by the EC, with nearly €80 billion of funding available over 7 years (from 2014 to 2020). **Framework Programmes (FPs)** were instrumental in that respect. The current FP (H2020) represents most of the implementation of the EC strategy entitled "***Innovation Union***"[31]. This strategy aims at securing Europe's global competitiveness by the creation of an innovation-friendly environment that makes it easier for ideas to be turned into products and services, with the clear ambition to enhance European economic growth and job creation. Through H2020, the Commission intends to ensure that Europe produces world-class science, removes barriers and makes it easier for the public and private sectors to work together in delivering innovation, as well as Erasmus+ coverage of research[32].

Also Public Private Partnerships (**PPPs**) are of strategic importance for the European industry. The EC indicates that PPPs will leverage more than €6 billion of public investments with each euro of public funding expected to trigger additional investments to develop new technologies, products and services, therefore aiming at consolidating the European industry as a leader on world markets. These PPPs are based on roadmaps for RTDI activities which are the result of an open consultation process and have been positively evaluated by the European Commission with the help of independent experts: PPPs started being implemented through open calls under H2020, and the first Work Programme for 2014-15, allocated around €1.45 billion for eight PPPs, including one with the Factories of the Future (**FoF**). The FoF multi-annual roadmap for the years 2014-2020 sets a vision and outlines routes towards high added value manufacturing technologies for the Factories of the Future, which will be clean, highly performing, environmental friendly and socially sustainable and with the engagement of the EU manufacturing industry: PPPs are expected to deliver the technologies needed for the new sustainable and competitive factories of the future. Another direct support to the development of the European Industry is related to the identification of KETs.

2.2 Key Enabling Technologies and Additive Manufacturing

As part of its strategy, the European Union mandated a High Level Group (HLG) [33] charged with the identification and selection of technologies that are expected to be decisive in tomorrow's economy. The focus was placed on horizontal technologies "enabling" multiple sectors, also called **Key Enabling Technologies (KETs)**. The six retained KETs[34] have the potential to increase the productivity and the energy efficiency of the industry, leading to competitive advantages and a cleaner European industry. These technologies are concerned with the so-called "*Valley of Death*" challenge justifying public intervention. In the European context, this **Valley of Death** is mainly seen at the level of demonstration and close-to-market activities. **Advanced Manufacturing Technologies (AMT)** – which **Additive Manufacturing (AM)** is part of – are one of the KETs showing great potential. In order to foster the development and commercialisation of AMT, a Task Force was set up by the European Commission in 2013. Its emphasis was put on the challenge facing the **commercialisation** of AMT- enabled products and the further **deployment** of this range of technologies.

One of the most promising segments of AMT (with "*particularly high growth*" and a global market volume expected to reach $ 11 billion in 2021[35]) is 3D-printing, also seen by many as the upcoming "*New "Industrial Revolution*"[36] leading to "*High performance manufacturing*". 3D-Printing in that context is usually called Additive Manufacturing, mainly referring to a set of dominant processes showcased in Table 5 and their mobilisation in an industrial context.

[30] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2010:2020:FIN:EN:PDF
[31] http://ec.europa.eu/research/innovation-union/index_en.cfm
[32] http://www.welcomeurope.com/european-funds/erasmus-plus-813+713.html#tab=onglet_details
[33] http://ec.europa.eu/growth/industry/key-enabling-technologies/european-strategy/high-level-group/index_en.htm
[34] Micro and nano-electronics, nanotechnology, industrial biotechnology, advanced materials, photonics, and advanced manufacturing technologies.
[35] Commission Staff Working Document SWD (2014) 120 final entitled "'Advancing Manufacturing – Advancing Europe' – Report of the Task Force on Advanced Manufacturing for Clean Production", 2014.
[36] Among many other examples, see http://www.economist.com/node/21552901 and http://www.businessinsider.com/the-next-industrial-revolution-is-here-3d-printing-2014-8?IR=T

Additive Manufacturing (AM) was indeed defined by ASTM International F42 committee as the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies"[37].

Table 5: Classification of AM processes

Process Type	Technique Definition	Example Technology	Material
Vat Photopolymerisation	Liquid photopolymer in a vat is selectively cured by light-activated polymerisation.	Stereo lithography (SLA), digital light processing (DLP)	Polymers and ceramics
Material Jetting	Droplets of build material are selectively deposited.	3D inkjet printing	Polymers and composites
Binder Jetting	Liquid bonding agent is selectively deposited to join powder materials.	3D inkjet printing	Metals, polymers, and ceramics
Material Extrusion	Material is selectively dispensed through a nozzle or orifice.	Fused deposition modelling (FDM)	Polymers
Powder Bed Fusion	Thermal energy selectively fuses regions of a powder bed.	Selective laser sintering (SLS), Selective laser melting (SLM), electron beam melting (EBM)	Metal, polymer, composites and ceramics
Sheet Lamination	A process in which sheets of material are bonded to form an object.	Ultrasonic Consolidation (UC)	Hybrids, metals and ceramics
Directed Energy Deposition	A process that focused thermal energy and fuses materials by melting as the material is being deposited.	Laser metal deposition (LMD)	Metals and hybrid metals

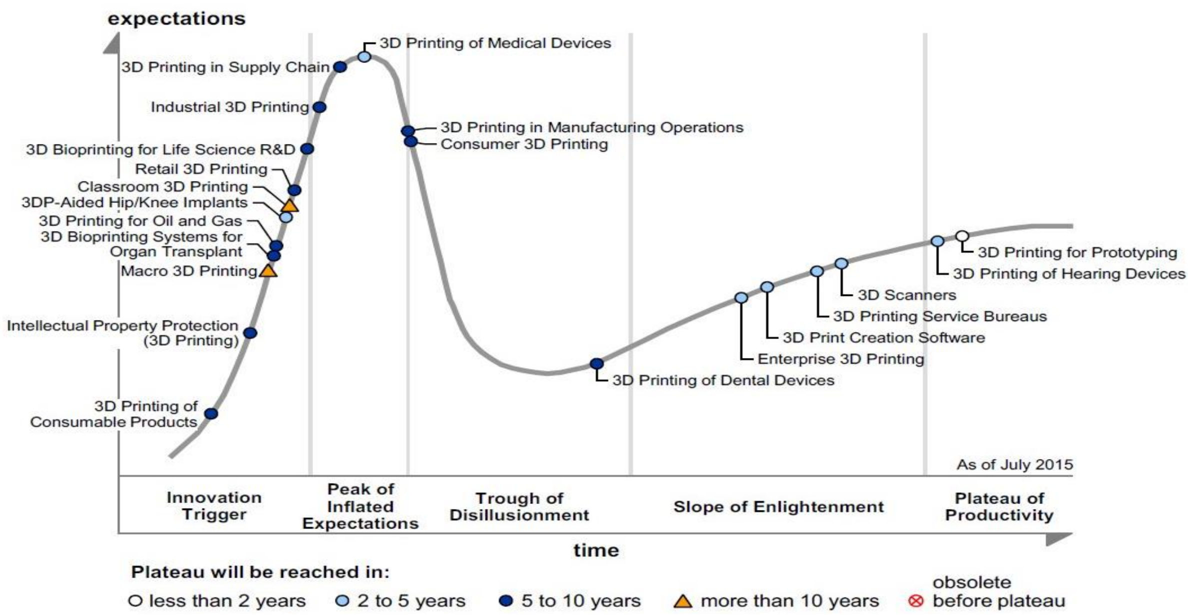
Source: EC AM Workshop report 2014

As for other AMT, additive manufacturing is concerned with its integration with other value chains because of its horizontal function in production processes. With **multi-sectorial applications**, it can enable the potential of industrial sectors to optimise their performance and the quality of their outputs. However, the AM landscape and European capabilities in particular appear to remain **fragmented** and **missing links** are observed **between** the **supply** and **demand** sides. The application of AM technologies has nonetheless been consolidating in different application areas such as in the medical, automotive and aerospace sectors, but many other application fields remain under-explored which might cover untapped AM potential.

2.3 The growth of 3D-Printing and the digital single market

AM is seen as a differentiating technology but due to its success in the media, it has also been the victim of a recent "*hype*" illustrated by the so-called "*Gartner Hype Cycle for 3D-printing*" (2015)[38] showcased in Figure 1. This figure illustrates the maturity of certain applications and the constant development of new "*innovation triggers*" as to counterbalance less realistic expectations.

Figure 1: The so-called "Hype Cycle for 3D-printing"



Source: Gartner, 2015

[37] See also http://www.astm.org/FULL_TEXT/F2792/HTML/F2792.htm
[38] https://www.gartner.com/doc/3100228/hype-cycle-d-printing-

According to the newly released Wohlers Report 2016[39], the AM industry[40], grew by 25.9% (compound annual growth rate - CAGR[41]), reaching $5.165 billion in 2015. The CAGR for the previous three years was 33.8% and over the past 27 years, the CAGR for the industry registers a score of 26.2%. The **AM industry is growing** by more than $1 Billion for the second consecutive year. As AM is based on Computer-Assisted Design (CAD), one of the key drivers of this growth relates to the development of ICT and the digitisation of industry and related services. The recent "*Path to digitise European industry*"[42] elaborated upon by the European Commission points to that direction: the EC plans to set up a European cloud that, as a first objective, will give Europe's 1.7 million researchers and 70 million science and technology professionals a virtual environment to store, manage, analyse and re-use a large amount of research data.

In addition, the EC will invest €500 million in a pan-EU network of **digital innovation hubs** (centres of excellence in technology). In these hubs, businesses can obtain advice and test digital innovations and set up large-scale pilot production projects to strengthen internet of things, advanced manufacturing and technologies. The objective would be to address the fragmentation of European markets in order to "*reap the benefits of digital evolutions such as the internet of things*" [43]. Such strategy echoes the European Economic and Social Committee (EESC) request to give priority to investments in ICT infrastructure, while evaluating the challenges and opportunities represented by Additive Manufacturing[44]. From that point of view, digital transformation allows and enhances the smart integration of services and products. Key industries such as engineering, automotive, healthcare and pharmaceuticals are increasingly impacted as value is shifting rapidly along the value chain: the transformative power of **Industry 4.0**[45] is based on the combination of digital technologies with other advanced technologies such as AM, in order to achieve maximum resource efficiency and boost EU competitiveness.

2.4 Adding the regional dimension: from the Vanguard 3DP Pilot to the present study

In the last two years several projects have investigated both cross-cutting KETs (such as the RO-cKETs project[46]) and 3D-printing in particular. Among other initiatives is the **Vanguard Initiative Pilot on 3D-printing**[47]**.** The Vanguard Initiative[48] is a '***bottom-up** initiative*' started by 20 EU regions in line with the European Cohesion Policy[49] and related smart specialisation strategies[50]. Among other pilots, the 3D-Printing Pilot of the Vanguard Initiative aims **at mapping and connecting demonstration capabilities** of European regions by linking segments of the 3D-printing value chain(s) across regions. A main objective of the Vanguard "*3DP pilot*" is to identify integration opportunities along and across industrial value chains. It was understood from the Vanguard experience that the regional scope was adapted to the need to combine strengths of various European innovation ecosystems to support AM adoption and deployment. Other sources of evidence such as the KETs Observatory[51] suggest that regions in Europe perform in a variable way when coming to AMT. This is in that context that this study was commissioned by the EC. The three main goals of the study were:

1) To identify key current and emerging (including future) **application areas** in the field of AM;
2) To reconstruct the underlying **value chains** at the regional level by identifying and positioning relevant European players;
3) To identify **missing competences** with regard to applications with a promising potential as well as collaboration opportunities to overcome the current and upcoming **barriers** to AM deployment in their respect.

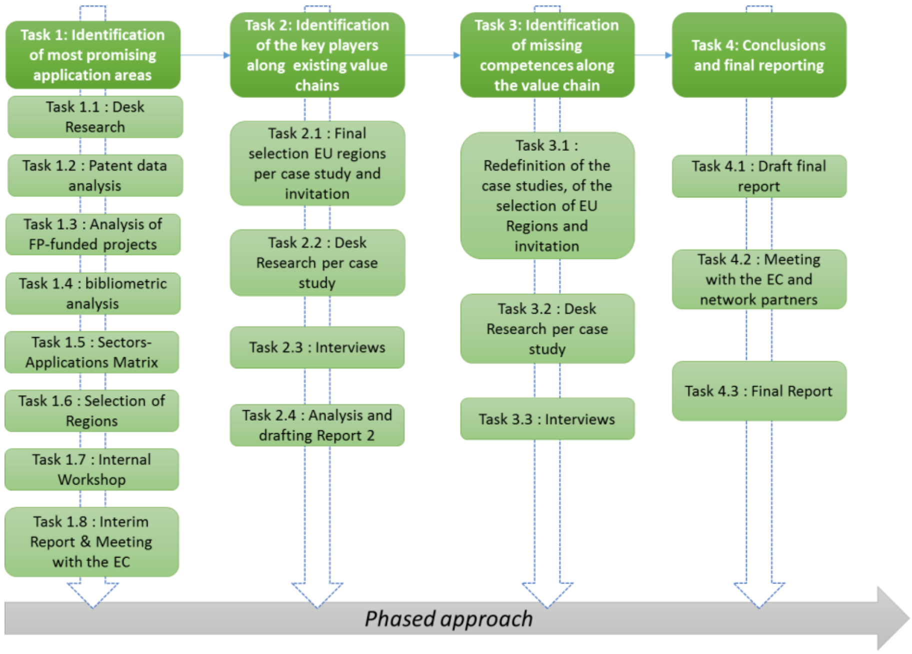
In line with the initial Terms of Reference for this study, the identification of missing competences and also new opportunities should constitute a solid basis for future cooperation between European regions in the benefit of the development of European 3DP-related strengths and the emergence of new ones.

[39] https://wohlersassociates.com/2016report.htm
[40] Which consists of all AM products and services worldwide
[41] http://www.investopedia.com/terms/c/cagr.asp
[42] http://ec.europa.eu/growth/tools-databases/newsroom/cf/itemdetail.cfm?item_id=8785
[43] http://europa.eu/rapid/press-release_IP-16-1407_en.htm
[44] http://www.eesc.europa.eu/?i=portal.en.ccmi-opinions.32834
[45] https://www.bundesregierung.de/Content/EN/Reden/2014/2014-02-19-oecd-merkel-paris_en.html
[46] http://ec.europa.eu/enterprise/sectors/ict/key_technologies/ro-ckets/index_en.htm.
[47] http://www.s3vanguardinitiative.eu/sites/default/files/contact/image/ssp_adma_pilot_3d_printing_network.pdf.
[48]http://www.s3vanguardinitiative.eu/sites/default/files/contact/image/ssp_adma_pilot_3d_printing_network.pdf.
[4949] http://ec.europa.eu/regional_policy/sources/docgener/informat/basic/basic_2014_en.pdf
[50] http://s3platform.jrc.ec.europa.eu/
[51] https://ec.europa.eu/growth/tools-databases/kets-tools/kets-deployment

2.5 Research process, approach and methods

The figure below depicts the **overall approach and process** designed for this study. From a content point of view, the four Main Tasks of this project ranged from the identification of most promising application areas to the identification of key players along the value chain and the identification of missing competences in the field of Additive Manufacturing. Each of these Main Tasks relied on a number of pillars, or sub-tasks, which are reminded in the figure as "*Tasks*".

Figure 2: Overall approach to this study



Source: IDEA Consult, 2015

The approach set out for this study relied on **both qualitative and quantitative methods**. These were combined in order to provide an overview of key application areas (connected to economic sectors) and identify value chain components and related players. The overall research process was to lead to an improved understanding of current and emerging AM value chains in Europe, as well as to the identification of trends and missing capabilities but also opportunities for public support to play a differentiating role (by undertaking initiatives to foster joint collaborations for instance).

Task 1. The first task was dedicated to the identification of key application areas, key emerging and future application areas, as well as key AM players in Europe (including Research and Technology Organisations [RTOs] and companies). Task 1.1 to Task 1.4 were mainly oriented towards the selection of a list of European regions with (mainly) AM supply capabilities. Task 1 was therefore subject to the implementation of **multiple research methods**, including a large-scale desk research, patent data analysis, the analysis of FP-funded projects, and bibliometric analysis. All outputs from these tasks were integrated by Task 1.5 into a large-scale matrix called ***"Sectors-Applications Matrix"*** **(SAM)** and available in Annex 2. This matrix was used in order to organize the relevant data per application area (an application area being the combination of a technical application with a specific economic sector). In parallel, regional profiles were drawn on the basis of existing data in the context of Task 1.6 to identify the demand potential per sector in each European region. The information gathered and synthesized in that context was to complement the outputs from the other tasks and compiled in the SAM. In practice, all aggregated information led to the selection of a long list of 25 application areas possibly interesting for further research. This first selection took place during a workshop organised at the consortium level. The list was then shortened to 10 application areas to be further investigated through Task 2 and Task 3 in the context of in-depth value chain case studies. This final selection was operated in Task 1.8 and in close collaboration with the services from the Commission.

Task 2. Task 2 mainly consisted in the implementation of the **first phase of the case study research**. A refinement of the case units was operated in the context of Task 2.1. Every case was to be a combination of an application area combined with related regions (for instance, German regions where a concentration of automotive activities can be observed were most likely to be included in an automotive case as potential AM users). When the final list was validated by the EC, desk research (mainly web-based) was conducted as well as semi-structured interviews in order to identify key AM players in Europe. The identification of these players and their activities was to lead to the identification of AM value chain segments for each of the selected cases. Information on the geographical repartition of these actors was to be highlighted as to better illustrate the relative weight of specific EU regions along each value chain.

Task 3. A **second phase of case study research** was to emphasize the emergence of new application areas as well as the barriers to the adoption and further deployment of AM along the selected value chains. A main output to come out from the finalized case studies was to be "policy implications" highlighted needs for public support, in particular when these would be related to joint action opportunities across EU regions. This task was partly conducted in parallel to Task 2 and called upon desk research as well as complementary interviews and written feedback from experts and industrial players.

Task 4. In order to conclude the project, Task 4 was dedicated to the **reporting** of the results. 3 interim reports were submitted along the project, which was closed after the present fourth (and final) report was submitted. In order to ensure the first step towards the dissemination of the results of this project, a workshop was also organised gathering the European Commission, representatives from the research consortium as well as key European experts and practitioners from the field of European AM policy.

The results of this study are presented in Sections 3/and 4/. These encompass all results from Task 1 to Task 4 and therefore include the analyses and findings from all quantitative and qualitative methods of enquiry.

3/ Europe and Additive Manufacturing: qualitative and quantitative analyses

3.1 Desk Research

A comprehensive desk research carried out by domain experts aimed at identifying the most important current and future sectors and applications that will be affected by 3D-printing. This review included a survey of recent scientific articles, conference papers, and other documentary sources. It intended to constitute a first basis to be complemented by quantitative analyses. 150 relevant papers were classified together with web-based sources, reports and analyses. 3D-printing applications, sectors as well as other relevant information were extracted to complete a first draft version of the Sectors-Applications Matrix (available in Annex 2). Main criteria to select the most important and relevant applications and sectors were the "*added value that Additive Manufacturing brings in*"[52], the "*Maturity of the area*"[53], and the existence of enough organisations (within the supply chain) working in the field so that dynamic progress in that field would be more likely to take place.

AEROSPACE. According to the Wohlers report 2015, Aerospace covers 14.8% of the revenues of 3D-printing industry (i.e. machines, materials and services) which mainly concerns aircrafts and spacecraft's' manufacturing. 3D-Printed parts are currently flying on airplanes, rockets and satellites[54]. Besides Space, aircraft manufacturing is relevant to Additive Manufacturing (AM) as it is concerned with the production of low volumes, complex and demanding components. Optimization through weight reduction and the reduction of the buy-to-fly ration are therefore main drivers of AM in the industry. Manufacturers aim at using topological optimization to build lighter parts in order to make savings on fuel consumption without reducing the performance of the components. Part consolidation but also cost, waste and cycle time reduction[55] are seen as main opportunities in this heavily regulated industry. In addition to non-structural parts, large companies such as Airbus, Boeing and GE Aviation took advantage of 3D-printing to produce components such as brackets, fuel nozzles, or air ducts. Repair and hybrid manufacturing[56] are intensively studied, covering particular issues such as the resistance of aerospace products to high temperatures (>2000°C) and harsh environments. On-site printing of parts (including moon-based 3D-Printing) is one of the long-term tracks followed by the companies active in the field.

AUTOMOTIVE. The automotive sector is concerned with passenger cars, trucks, busses, as well as light commercial vehicles, excluding special vehicles like tractors, cranes and other similar vehicles. Since their initial adoption of 3D-Printing around 1988, car manufacturers developed rapid prototyping to improve development cycles. The motor vehicles sector currently corresponds to 16.1% of Additive Manufacturing usage and is expected to expand (Wohlers, 2015). As typical production volumes in the automotive industry are too high to economically produce final parts with AM, its use remained limited to prototyping and tooling. Personalization and customization but also new requirements to have eco-efficient cars are however attracting the interest of car manufacturers in AM. Not only light-weight and energy efficient components are relevant to AM, but also the possibility to reduce the production time of new car models such as functional prototypes by reducing the needs for tooling and assembly. Several cases can be observed in special and racing car industries where AM was used for optimization. The most illustrative example of the future of automotive AM remains Local Motors, an US-based company which announced a launch of a "*3D-printed electric car*"[57] directed to customer markets.

HEALTHCARE. The medical and dental sectors correspond to around 13.1% usage of Additive Manufacturing (Wohlers, 2015) and are particularly driven by personalisation or mass customisation. This sector is heavily regulated, which slows down the utilisation of new technologies and especially materials. Products are however being 3D-printed, sometimes in large proportions such as hearing aids (more than 10 million are printed every year). AM offers the possibility to have a simplified production chain consisting in three steps instead of nine and to obtain fully dense and porous structures that allow better fixation of implants. Tens of thousands of 3DP-fabricated metal implants are produced every year. Acetabular cups and (in the dental area) invisaling dental braces but also crowns are probably the most well-known 3D-printed products[58]. They are however not the only ones as surgical visualisation aids, simple tools and preoperative models derived from 3D-scans are also being printed in the medical industry. Cost savings are even obtained thanks to the simplification of the production process of products such as prostheses. On the longer-term bio-printing or tissue engineering (also called organ printing)[59] and drug printing (including smart medicine and micro-factories) are expected to become a major field.

[52] Business drivers relevant for an application were to be strong enough to overcome the potential current drawbacks of the advanced manufacturing technology.
[53] The focus was on applications assumed to reach commercial stage approximately after 3-5 years.
[54] The ESA listed potential parts to be produced by Additive Manufacturing: different structures, multifunction casing, RF filters, optical base plate, bracket and injectors as well as various on demand tools.
[55] Through the printing of parts in a single piece instead of several fitted together – which can lead to savings on assembly costs.
[56] Technologies combining conventional machining.
[57] The production of mechanical components such as the battery and the motor of each car is however being outsourced.
[58] Several millions of molds are actually printed every year in the dental area.
[59] According to Murphy and Atala, two-dimensional products (like skin) will be first applications, followed by hollow tubes (blood vessels etc.), hollow organs and finally solid organs.

MACHINES & TOOLING. This sector covers the manufacturing of industrial and business machines as well as all kinds of tooling. Computers, routers, CNC machines, robots, etc. are therefore under the scope of this sector. This sector covered 17.5 % of AM in 2014 (Wohlers, 2015) and mainly involved AM for product development and the production of low-cost tools. Examples of heat exchangers and robot arms could be identified. The interest of AM for machines and tools mainly lies in the possibility to customize and produce lightweight parts, internal channels/structures, reach functional integration, design surface structures, or benefit from specific material options. Quality products can indeed be printed with a reduced level of scraps. Currently, companies such as Matsuura and DMG Mori (Japan/Germany), Hermle (Germany), Mazak (Japan), Optomec (USA), and Hybrid Manufacturing Technologies (UK) offer hybrid machines and services developed to optimize the use of AM for tool printing by combining it with conventional technologies such as CNC. AM is therefore used to manufacture mold inserts, sheet metal tools, robot grippers, patterns for sand and investment casting, and fixtures and jigs for welding and assembly.

ELECTRONICS and ELECTRONIC DEVICES. Direct Write technologies allow for the printing 2- or 3-dimensional structures such as antennas and many kinds of electronic circuitry directly onto flat or conformal surfaces in complex shapes, without any tooling or masks. A good example is printing on mobile phone covers. The Aerosol Jet system from Optomec (USA) was for instance used to print a conformal sensor, antenna and circuitry directly on a FDM-printed wing of an unmanned aerial vehicle model. Together with the use of conductive and graphene filaments, the conductivity of metal-based inks (especially those based on silver) is seen as better than with carbon-based filaments. The newest development in the area is to co-print FDM filament and conductive ink and to produce functional objects using only one printer. According to Voxel8, picking and placing functional objects will be automated in the future and better combinations of techniques will be found. Also embedded stereolithography[60] for the flexible manufacturing of mechatronic modules is under research in Germany. Developments such as complex shapes printing or two photon polymerisation are mainly driven by the challenge of thermal management which is constrained by miniaturisation of electronic devices.

CONSUMER LIFESTYLE & FASHION (incl. TEXTILES & CREATIVE INDUSTRIES). Two AM-related areas can be identified: (1) 3D-printed industrial products; and (2) consumer 3D-printed products (e.g. toys, avatars, home decoration etc.). A hype related to the latter has brought a lot of public visibility to consumer 3D-printing which is mainly driven by the possibility to print series of one. Jewelleries are currently being printed with precious metals such as gold and silver and can be customized or made with complex shapes. This value chain is being disrupted by the availability of customized jewels designed by independent entrepreneurs. In the fashion sector (textiles, shoes, garments) 3D-printing is for instance used to create eye-catching dresses and bikinis based on hard polymers or accessorised garments. Comfort and flexibility of the textile for garments are however to be further researched in order to produce truly wearable apparel for daily use. New materials and multi-material printing are being explored. AM was also used to develop better cleats for football shoes and tennis products. The ability to print full colours and the safety of materials are critical factors in this area.

OIL & GAS. This industry is concerned with the value chain ranging from the exploration to the distribution of petroleum products. In particular the production in remote locations would be relevant to the printing of spare and wear parts on site. Also extreme environments such as ultra-deep-water or arctic environments create the need for adapted equipment. Pumps, pipelines, valves, drills etc. could also be optimised, but the size allowed by most AM techniques remains limited compared to the size needed for such components. In addition, the quality and strength of the components does not yet fulfil the resistance requirements of this sector. Although it remains focused on prototyping, examples exist of gas turbines, fuel nozzles, smart pipeline inspection gauges (PIG) and drilling pro ducts that are being printed by companies such as General Electrics or Halliburton. These players make important investments in additive technologies. Sensors and subsea pumps are seen as the upcoming applications to be 3D-printed (sensors are even at an early use stage).

ENERGY. Companies such as Siemens Power Service or General Electrics are known to use AM for rapid prototyping, repair and the on-site production of turbine blades and burner tips. Time to market, repair times a,d overall lead time reductions were achieved. Also the life time and efficiency of complex parts was improved thanks to the printing of cooling channels. According to the MIT, 3D-printed solar panels could achieve 20% more efficiency compared to flat solar panels. In addition, 50% savings could be achieved on expensive materials used for solar panels such as glass, polysilicon and indium. These savings could be passed on to the consumers, making the switch from fossil fuels to solar energy more appealing. 3D-printed organic solar cells capable of powering a skyscraper could even be developed in the future. Also thin solar cells could be printed on untreated paper, plastic or fabric could be printed instead of using expensive glass. Solar panels could be made flexible, lighter, and with a reduced prototyping time. Selective Laser Sintering (SLS) is already used to print micro fuel cells, but new applications arise such as small-scale 3D-printed wind turbines, Pelton turbines for small-scale hydropower experiments, and possibly nuclear and fusion power components.

60 The method combines Stereolithography and UV-laser sintering of silver ink.

CONSTRUCTION. The University of Southern California initiated the concept of "*Contour Crafting*" while the Loughborough University developed "*Concrete printing*". Both are seen as foundations of the current construction 3D-printing area which is concerned with the printing of facilities and structures. This area is subject to different technologies (using concrete for instance) compared to other sectors. It is in a demonstration phase and knows three main drivers: the possibility to build more affordable houses (which usually relates to automation and the redundancy of formworks and scaffolds), to build on-the-spot emergency houses as well as to increase architectural flexibility. According to Lux Research, the nearest commercial maturities are glass, lighting and furniture applications. The printing of frameworks, foundations and flooring are at a concept level, while the development level includes exterior and interior walls and heating, ventilation and air conditioning (HVAC) systems. Efforts are made in this field: bridges are for instance being printed in the Netherlands. The University of Nantes (FR) is currently developing a concept related to (emergency) sealed and insulated shelters to be printed in 20 to 30 minutes with dimensions of 3 meters high by 3 square meters. Not only full house printing is under the scope but also the development of modular systems (3D-printed of "*bricks*" or walls modules). The Chinese company Zhuoda Group has filled 22 patent applications related to their module house concept, where the modules are printed elsewhere and then shipped to building location for final assembly.

MILITARY. The applications in the military sector overlap with other sectors, such as healthcare, and aerospace. On-demand and on-site production of spare parts is a key development area. Examples include 3D-printing printing on ships, or shelter printing in remote areas. In addition to mobile factories also field hospitals are of interest to defence forces. One example under development is printing skin cells onto burn wounds.

TRANSPORTATION (MARINE & SPECIAL VEHICLES). Several research investments to develop the use of 3D-printing in this sector as well. For instance, Hyundai Heavy Industries has invested in South Korea in an innovation centre which focuses on the use of 3D-printing in the marine industry. In the Netherlands, a consortium of 27 companies in the marine industry has kicked off a new project focusing on the 3D-printing of spare parts for the marine industry. The availability of information on potential applications remains limited at this point of time.

FOOD. The first chocolate printer was commercialized in 2014 and some experts from the Institute of Food Technologists (IFT) predicts that 3D-printers have the potential to revolutionise the way food is manufactured within the next 10 to 20 years. Homes and small cafes are the main (though not only) targets. The world first 3D-printed food conference was organised in 2015, showcasing new shapes and other benefits brought by AM to food processing. Customised food for various groups with different nutrient contents could be 3D-printed[61]. Also customised/personalised structures and flavours and the production of food in remote locations are seen as opportunities. In addition, printers are being researched for sugar, ice-cream, pizza, pasta, vegetables, pancake, lollipops, chewing gum, and other food products. Concepts are also being developed regarding the 3D-printing of whole dishes.

MISCELLANEOUS. Other areas are subject or are expected to become subject to additive forms of manufacturing whether currently or in the near future. Among other examples is the one of optics: new approaches are being developed to print glass or plastics with good optical properties (such as needed for lenses, optical fibres etc.). 3D-printing is also used in industries such as entertainment, movies and game industries where personalised products are printed to speed up digitization.

3.2 Patent data analysis

A patent analysis was conducted in combination with the desk research as to identify industrial players who are located on the "*supply*"[62] side of European AM value chains. The analysis was to feed in the Sectors-Applications Matrix (or SAM, see Annex 2) used to classify the application areas organised per sector. In the context of the patent data analysis, the number of patents and the time since their official filing served as indicators for the significance of the firm. Relevant studies analysing patents in the field of AM were analysed and used as a source of inspiration for the present study – although the search strategy and time periods for this study differ[63] from the others of course. Gridlogics (2014) and an IPO study limited to 2013 were used in the context of the following analysis and were complemented by an additional patent analysis based on the EPO database[64]. The analysis of the new patent class B33Y Additive Manufacturing on the EPO database revealed that until the end of August 2015 no patent have been published so far.

[61] For instance different food for athletics and different food for pregnant women.

[62] Producers of equipment, material, facilities, etc.

[63] Wohlers Report 2015: Trends. Analysis. Forecast. 3D-printing and Additive Manufacturing. State of Industry. ISBN 978-0-9913332-1-9 Intellectual Property Office, 3D-printing: A Patent Overview (Newport: Intellectual Property Office; November 2013) https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/312699/informatics-3d-printing.pdf 3D-printing: Technology Insight Report (2014)¸ Gridlogics Technologies Pvt Ltd; http://www.patentinsightpro.com/techreports/0214/Tech%20Insight%20Report%20-%203D%20Printing.pdf

[64] One should also note that on the 1st of January 2015 a new patent subclass was introduced by the WIPO (World International Property Organisation) specifically dealing with Additive Manufacturing. This subclass alone is however not sufficient yet as it is too recent.

In addition, one should note that there is evidence of intellectual property infringement, at present on a small scale, which highlights the potential for future intellectual property issues[65]. The findings from the two most relevant patent analyses are summarised in this chapter along with updated data from the consortium's own investigation. The respective search algorithms are summarised in annex (see Annex 4). The results of these analyses were added to the Sectors-Applications Matrix (see Annex 2) which served as main repository for the selection of the value chains to be studied in-depth in the context of case studies (see Section 4/) . The activities of the companies identified by the patent studies and the complementary analysis have been analysed in more details and were added to the Matrix.

RESULTS. Table 6 hows the top patent applications in the field of 3D-printing. While some historical patent holders (such as Fujitsu and NEC) have restricted their patenting activities, other top applicants such as Stratasys and Corp Z have filed for patents in this area only relatively recently or recently entered the technology space (e.g. Objet Geometries since 1989). Other applicants simply stopped patenting (e.g. LG Phillips after 2004). The top 2 applicants – Stratasys and 3D Systems Inc. (3DS) – started patenting in 1993 and 1990 respectively and progressively absorbed companies from the AM market, including their IPR.

Table 6: Top patent companies with 3D-printing patents (European Companies in cursive)

Patent Assignees (Gridlogics[66]) 1990-2013	Total No. of Published Patents	Patent Assignees (IPO[67]) 1980-2013	Total No. of Published Patents
3D Systems Inc	**39**	3D Systems Inc[68]	**91**
Stratasys Inc	**37**	Stratasys Inc [69]	**92**
Massachusetts Inst. Tech	**30**	Fujitsu Ltd[70]	**92**
Hewlett-Packard Co	**26**	NEC Corp	**67**
Hitachi Chem. Co Ltd	**26**	Samsung Electronics Co Ltd	**48**
Matsushita Electric Works Ltd	**24**	*LG Phillips LCD Co Ltd*	**41**
Therics Inc	**23**	Object Geometries Ltd	**38**
Materialise NV	**22**	Univ. Texas System	**36**
Objet Ltd	**20**	Boeing Co	**34**
Panasonic Corp	**20**	Z Corp	**34**
IBM Corp	**19**		
The Boeing Co	**19**		
Mimaki Engg Co Ltd	**17**		
3Shape A/S	**15**		
Dainippon Printing Co Ltd	**15**		

Source: Gridlogics (2014), IPO (2013)

Table 7 depicts the results of the patent analysis in the most recent years between 2014 and 2015 based on an analysis of data from the EPO. European Aerospace companies (Rolls-Royce, BAE Systems, Airbus and SNECMA) successfully granted AM patents. Materialise N.V. (BE) comes in 7th position as one of the main European AM service providers, while Alstom Technology Ltd applies AM to gas turbines and power supply.

65 A Legal and Empirical Study into the Intellectual Property Implications of 3D-printing: Executive Summary; Published by The Intellectual Property Office March 2015; ISBN: 978-1-908908-85-8; https://www.gov.uk/government/publications/3d-printing-research-reports A Legal and Empirical Study of 3D-printing Online Platforms and an Analysis of User Behaviour; Published by The Intellectual Property Office March 2015; ISBN: 978-1-908908-96-4; https://www.gov.uk/government/publications/3d-printing-research-reports The Current Status and Impact of 3D-printing Within the Industrial Sector: An Analysis of Six Case Studies; Published by The Intellectual Property Office March 2015; ISBN: 978-1-908908-86-5; https://www.gov.uk/government/publications/3d-printing-research-reports Bradshaw, S., Bowyer, A. and Haufe, P., 2010. The intellectual property implications of low-cost 3D-printing. ScriptEd, 7 (1), pp. 5-31.

66 3D-printing: Technology Insight Report (2014)¸ Gridlogics Technologies Pvt Ltd; http://www.patentinsightpro.com/techreports/0214/Tech%20Insight%20Report%20-%203D%20Printing.pdf

67 Intellectual Property Office, 3D-printing: A Patent Overview (Newport: Intellectual Property Office; November 2013) https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/312699/informatics-3d-printing.pdf

68 3D Systems has merged with Z Corp, and Vidar systems amongst others, the patents were added up in this study.

69 Stratasys has merged with Objet and MakerBot Industries, the patents were added up in this study

70 Fujitsu has not been active in this area for some time, though, the granted patents owned by Fujitsu will soon expire.

DSM IP Assets B.V. is active in various global fields[71] while Michelin is developing metal Additive Manufacturing and very recently (September 2015) joined up with the AM specialist Fives to form FIVES MICHELIN ADDITIVE SOLUTIONS[72]. Blueprinter ApS in Denmark develops an easy to use 3D-printer affordable even for very small businesses. The Dutch LUXeXcel Holding B.V. focuses on optics and consumer products and Siemens AG is interested in applications of 3D-printing for Healthcare, Energy and Electronics.

Table 7: List of top companies (2014 - 2015) (European companies in cursive)

Company Name	Patent Assignees 2014-2015
▶ *Rolls-Royce*	11
▶ Samsung Electronics Co Ltd	11
▶ Honeywell International Inc.	10
▶ Stratasys Inc	8
▶ *Airbus*	7
▶ *BAE Systems PLC*	7
▶ *Materialise N.V.*	7
▶ *Alstom Technology Ltd*	6
▶ GENERAL ELECTRIC COMPANY	6
▶ Panasonic Corporation	6
▶ *DSM IP Assets B.V.*	5
▶ Hamilton Sundstrand Corporation	5
▶ LG Chem, Ltd.	5
▶ *Michelin*	5
▶ *SNECMA*	5
▶ 3D Systems Incorporated	4
▶ 3M Innovative Properties Company	4
▶ *Blueprinter ApS*	4
▶ FUJITSU LIMITED	4
▶ *LUXeXcel Holding B.V.*	4
▶ *SIEMENS AKTIENGESELLSCHAFT*	4

Source: EPO, own calculation

3.3 Analysis of FP-funded projects

As a basis for the identification of relevant key players and completion of the application fields listed in the Sectors-Applications Matrix (Annex 2), the consortium in charge of this study used the EUPRO[73] and CORDIS[74] databases to gather and analyse information on projects supported by the Commission under the 7th Framework Programme (FP7) and Horizon 2020. The overview was extended to FP4, FP5 and FP6 as well as INTAS[75]. Key words were used in order to identify EU projects dealing with 3D-printing and Additive Manufacturing[76]. The results were supplemented with further input from experts[77] and official information from EU websites. Table 8 provides an overview of the total number of relevant projects and the number of participants under each Framework Programme (FP).

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71 Such as food and dietary supplements, personal care, feed, medical devices, automotive, paints, electrical and electronics, life protection, alternative energy and bio-based materials with a focus on engineering plastics

72 FIVES MICHELIN ADDITIVE SOLUTIONS will be 50% owned by Fives and 50% by Michelin and will benefit from a financial contribution of at least €25 million in the first three years. http://www.fivesgroup.com/news-press/news/the-michelin-group-and-fives-join-forces-and-create-fives-michelin-additive-solutions-to-become-a-major-metal-3d-printing-player.html

73 This database contains comprehensive, systematic and revised information on more than 60,000 research projects (title, content, duration, cost, etc.) and their participants (name, type of organisation, location, contact person, etc.) from the first to the seventh EU Framework Programme.

74 http://cordis.europa.eu/search/advanced_de?projects

75 INTAS is an international association which promotes co-operation with scientists in the NIS, and complements the activities of Copernicus-2. It was set up in June 1993 as an independent organisation under Belgian law, and its members currently comprise the European Community, the EU Member States, Iceland, Israel, Latvia, Norway, Romania, Slovenia and Switzerland. As a non-profit, charitable association, based in Brussels and tax exempt, it is funded primarily through the Fifth Framework Programme, and carries out a large part of EU research activities with the NIS. https://ec.europa.eu/research/nis/en/intas.html

76 These were the following: "*3D-print*"; "*three dimensional print*"; "*additive manufac*"; "*electron beam melting*"; "*selective laser melt*"; "*selective laser sinter*"; "*fused deposition modelling*"; "*fused deposition modeling*"; "*stereo lithogra*"; "*stereolitho*"; "*three dimensional biopr*"; "*Bioprint*"; "*drug print*"; "*binder jetting*"; "*material jetting*"; "*sheet lamination*"; "*laser cusing*"; "*direct metal laser sintering*"; "*food print*".

77 The European Commission (RTD D.2) provided us with a list of EU projects dealing with 3DP which particularly complemented the results of the most recent projects funded within H2020.

Table 8: Overview of projects dealing with 3D-printing in the EU Framework Programmes

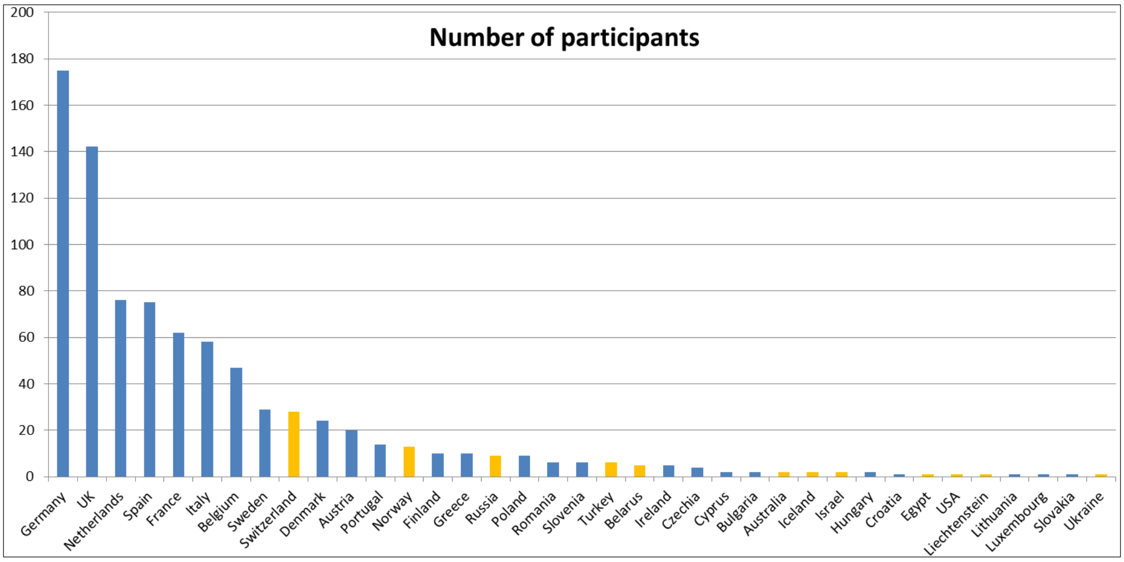
EU Programme	Number of projects	Number of participants
INTAS[78]	3	20
FP4	10	105
FP5	4	16
FP6	11	149
FP7	64	553
Horizon 2020	9	55**
Total	**101**	**602**

* The total number of participants eliminates partners that participated in different framework programmes
**H2020 is not completed yet in partner participations

Source: EUPRO database, CORDIS database, own calculation

RESULTS. 101 projects were identified of which a comprehensive list was added to the Annex 5. Most project partners originate from Germany, the United Kingdom, the Netherlands, Spain and France (see Figure 4). Companies and research organisation with the most involvement in FPs are listed in Figure 4. The 11 organisations with most projects (5-25) in the field of 3D-printing were evaluated in more depth. A cross table to investigate the relationship between these organisations can be found in annex as well. Information relevant to the thematic analysis was then added to the Sector Application Matrix.

Figure 3: Statistical overview of country participation in EU framework programmes



Source: EUPRO database, CORDIS database, own calculation

78 INTAS is an international association which promotes co-operation with scientists in the NIS, and complements the activities of Copernicus-2. It was set up in June 1993 as an independent organisation under Belgian law, and its members currently comprise the European Community, the EU Member States, Iceland, Israel, Latvia, Norway, Romania, Slovenia and Switzerland. As a non-profit, charitable association, based in Brussels and tax exempt, it is funded primarily through the Fifth Framework Programme, and carries out a large part of EU research activities with the NIS. https://ec.europa.eu/research/nis/en/intas.html

German players dominate the area. The Fraunhofer Gesellschaft zur Förderung der angewandten Forschung e.V. research institute (DE) was most active with an involvement in 25 projects (20 of them under FP7), collaborating with most of the other top 11 organisations except the AIMME and AJUI (ES). The Universities Würzburg, Nürnberg or Stuttgart and the Karlsruhe Institute of Technology KIT (DE) are the next German players in line together with companies such as Siemens, BMW, EADS or Lufthansa, as well as SMEs. Other main German players are BCT Steuerungs und DV-Systeme GmbH participated in 5 EU projects under FP7 and EOS GmbH Electro Optical Systems.

Figure 4: Organisations with most involvement in EU framework programmes (25-4 projects)

Source: EUPRO database, CORDIS database, own calculation

In the United Kingdom, Loughborough and Cambridge University are followed by The Welding Institute (TWI) and LPW Technology Ltd. In the Netherlands the strongest partners were TNO and Philips N.V. TNO took part in a wide range of projects, coordinating three of them. In Belgium, Materialise participated in some of the same projects. The most active research organisations in Spain were Metalworking Technology Institute, AIMME, AIJU Instituto Tecnológico de Producto Infantil y Ocio, and IBV, the Biomedical Institute of Valencia. These were followed by the Swiss INSPIRE AG is a strategic partner of the ETH Zurich, and Raufoss A/S, a company within the The Neuman Aluminium Group.

Overall, FP-supported projects investigated AM in areas ranging from energy to biomedical. From a technical point of view, one can note that metal, ceramics as well as multi-material AM were further researched – although metal-based AM seems to be most recurrent. Preoccupations vary depending on the project and players involved: from lightweight components in automotive and aeronautic sectors to the printing of electronics and organic materials, themes vary depending on the role the company takes in its value chain(s) as software, printer, or material developer. A summary of research projects funded in FP6, FP7 and Horizon 2020 of the most active research organisations can be found in the annexes which provides more details on the topics and themes investigated. A short description of the biggest projects, either in volume or in numbers of partners, is given next (see Table 7).

Table 9: Overview of the biggest EU-funded research projects and topics in line with the Applications of the SAM

Project	Sector and applications
AMAZE (**Additive Manufacturing A**iming Towards **Z**ero Waste & **E**fficient Production of High-Tech Metal Products); FP7 ▶ The goal of AMAZE is to produce large defect-free additively-manufactured metallic components (up to 2 meters) with close to zero waste (50% cost reduction for finished parts) used in the high-tech sectors aeronautics, space, automotive, nuclear fusion and tooling. ▶ The commercial use of adaptronics, in-situ sensing, process feedback, novel post-processing and clean-rooms in AM will be reduced (quality levels are improved, build-rates increased by factor 10, dimensional accuracy increased by 25% and scrap-rates slashed to 5%) ▶ The links between alloy composition, powder/wire production, additive processing, microstructural evolution, defect formation and the final properties of metallic AM parts will be examined	▶ Aerospace: Component repairing ▶ Aerospace: Non-structural parts for aeroplanes ▶ Automotive: Non-structural parts
ARTIVASC 3D (**Arti**ficial **vas**cularised scaffolds for **3D**-tissue-regeneration); FP7 ▶ ArtiVasc 3D will provide a micro- and nano-scale based manufacturing and functionalisation technology for the generation of fully vascularised bioartificial tissue that enables entire nutrition and metabolism. ▶ The bioartificial vascularised skin (engineered in ArtiVasc 3D) will allow tissue replacement with optimum properties. Vascularised skin will also be used as an innovative in vitro skin equivalent for pharmaceutical, cosmetics or chemical substance testing, which represents a promising method to reduce expensive, ethically disputed animal testing. ▶ ArtiVasc 3D will develop a combination of hi-tech engineering (micro-scale printing, nano-scale multiphoton polymerisation and electro-spinning) with biological research on biochemical surface modification and complex cell culture.	▶ Healthcare: Bioprinting / organ printing
BOREALIS (the 3A energy class Flexible Machine for the new Additive and Subtractive Manufacturing on next generation of complex 3D metal parts); H2020 ▶ Borealis project presents an advanced concept of machine for powder deposition Additive Manufacturing and ablation processes that integrates 5 AM technologies. The machine is characterised by a redundant structures constituted by a large portal and a small PKM enabling the covering of a large range of working cube and a pattern of ejective nozzles and hybrid laser source targeting a deposition rate of 2000cm3/h with 30 sec set-up times. Software infrastructure enables a persistent monitoring and in line adaptation of the process ▶ Aiming at TRL 6 for two complete Borealis machine in two dimensions – a lab scale machine and a full size machine – which are foreseen to be translated into industrial solution by 2019	▶ Machines & Tooling: Spare parts for machines ▶ Machines & Tooling: Proto-typing in product development of machines
CUSTOM-FIT (A knowledge-based manufacturing system, established by integrating Rapid Manufacturing, IST and Material Science to improve the Quality of Life of European Citizens through Custom fit Products); FP 6 ▶ CUSTOM-FIT drastically changes how and where products are designed and made. It creates sustainable, knowledge-based employment, which plays a critical role in safeguarding Europe's manufacturing industry by developing and integrating a completely new and breakthrough manufacturing process based on Rapid Manufacturing (RM) ▶ Three main technical breakthroughs: Automated design system for knowledge based design of Custom-Fit products, Processing of graded structures of different material compositions and Rapid Manufacturing for Instant and On-Demand manufacturing of graded Custom-Fit products. ▶ Enables a vertical integration in the value chain and horizontal integration by the ability to transfer the knowledge to other industrial sectors.	▶ Machines & Tooling

Project	Sector and applications
NAIMO (NAnoscale Integrated processing of self-organizing Multifunctional Organic Materials); FP6 ▶ NAIMO will develop new multifunctional materials that are processed by solution-based Additive Manufacturing (e.g. direct printing), under quasi-ambient conditions, to form a composite material with designed multifunctionality in an environmentally-friendly way. ▶ A key outcome of NAIMO will be the set of materials, process and manufacturing capabilities to transform a plastic film substrate into a multifunctional composite (with designed electronic, optical, sensing and magnetic capabilities).	▶ Healthcare

3.4 Bibliometric analysis

This bibliometric analysis was aimed at 1) providing an overview of a research topic and insight into scientific literature and 2) identifying relevant key players (both academic and industrial research players, top researchers and the connections between them). This analysis takes as a basis the number of scientific publications issued worldwide in any field of research[79]. An analysis of the network and connections between topics or actors was also conducted, allowing for the identification of topics or collaboration themes between organisations. More details about the methodology are provided in Box 7.

Box 7: Bibliometric analysis in practice

The calculations were done with the BibTechMon™ tool developed by AIT[80]. The computation of science maps is based on the two dimensional representation of the co-occurrence matrix of terms in the relevant literature (reviewed journals, conference proceedings, patents). The representation of the inter-term relations is done via a spring model and by clustering algorithms. Depending on the question of investigation, the map renders descriptors (keywords), extracted noun phrases (e.g. extracted from Abstracts and titles), actors (authors, organisations) or a combination thereof. By defining appropriate indicators, it is possible to identify emerging research fields or emerging or incumbent key players in the relevant scientific communities[81]. The basis of the analysis is data from the Web of Science™ publication database from Thomson Reuters[82]. The following search strategy was adopted for the time period 2010 until 09th July 2015:

- Topic=(3D-print* OR three dimensional print* OR 3D plot* OR additive manufac* OR stereolitho* OR stereo lithogra* OR direct metal laser sinter* OR drug print* OR 3d Biop* OR three dimensional biopr* OR electron beam melting OR Selective laser melt* OR Selective laser sinter* OR fused deposition modelling OR fused deposition modeling OR Laser cus* OR sheet lamination OR binder jetting)
- AND Document Type = (Article OR Book OR Book Chapter OR Meeting Abstract OR Meeting Summary OR Proceedings Paper OR Review)

4,713 recorded articles were identified and analysed. BibTechMon™ calculations led to the identification of networks based on co-object analysis. The research activity was measured by weighted number of local agglomerated similar publications. Similarity was measured by the Jaccard index of bibliographically coupled publications, and visualisation was performed with a spring model and number weighted by the similarities between publications.

RESULTS. Figure 5 depicts the scientific publication network where the height of peaks corresponds to the number of publications in a given field. The position of themes to each other is an indicator for how close or unrelated topics are. In total, we identified 11 peaks which are interpreted as research fronts.

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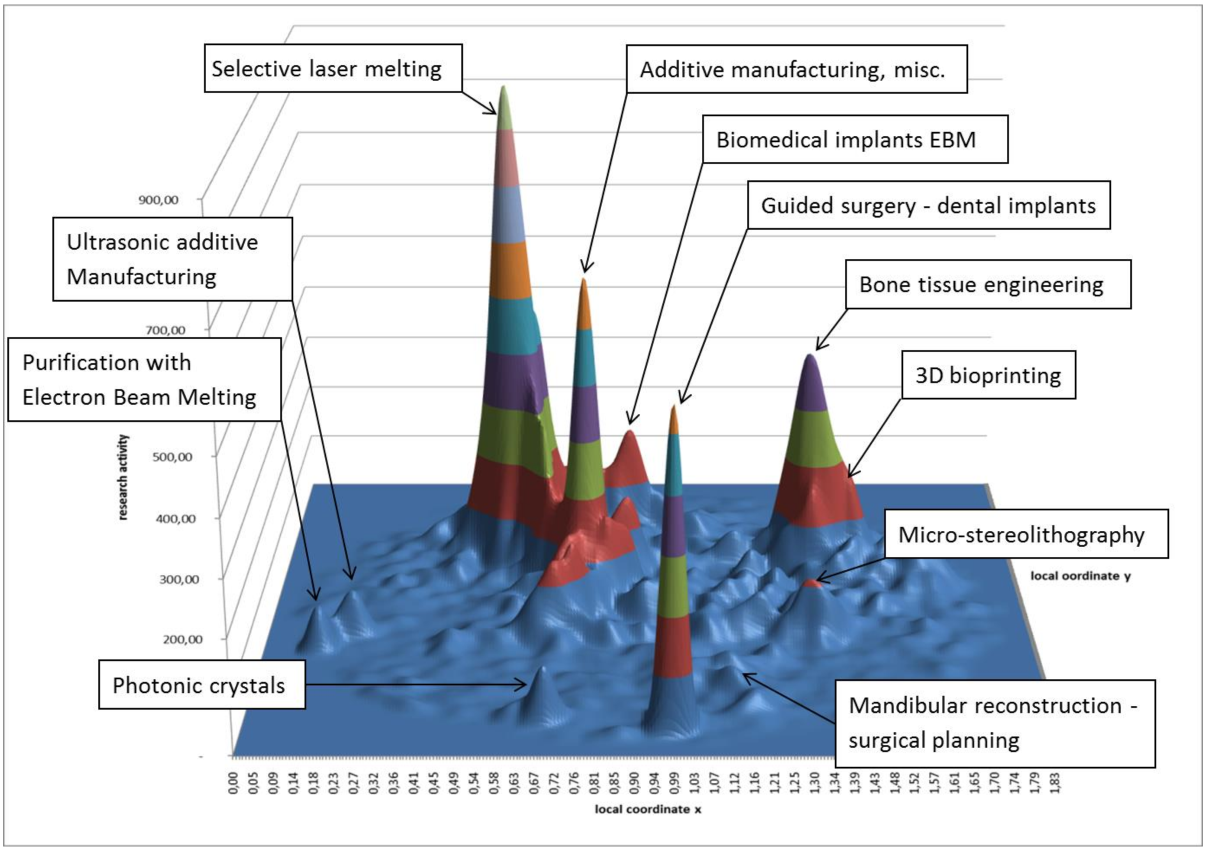
79 Consequently, high numbers of scientific papers on a particular technology in a certain area indicate high scientific activities and specialisation in this area, whereas low activities may result in technological dependencies on other regions concerning the particular technology.

80 Kopcsa A, Schiebel E. (1998). Science and Technology Mapping: A New Iteration Model for Representing Multidimensional Relationships. Journal of the American Society for Information Science, 49, 1, 7-17.

81 In case of this literature analysis an object (a node) is a paper. The "*size*" of a node is related to the number of cited references used in this paper. The more references a paper cites, the "bigger" the node is. Two papers share an edge if they cite the same reference. The more references two papers share, the closer they are related and thus are drawn together closer in the network. The nodes find their positions in the network graph based on their relations to all other nodes. This results in a network of nodes, where clusters of nodes dealing with similar topics are formed. Papers lying within these clusters can be studied whereby topics are identified and labelled. This results in a map of research areas and topics, with research fronts, clusters of highly cited papers, standing out.

82 The Web of Science™ is an online database and provides a citation databases and covers over 10,000 of the highest impact journals worldwide, including Open Access journals and over 110,000 conference proceedings with the focus on essential data across 256 disciplines.

Figure 5: Main research activities in 3D-printing and Additive Manufacturing



Source: Web of Science, own calculation

Table 10 summarises the distribution of publication numbers between continents. The number of publications is an indicator of how active research or industrial organisations are in each of the specified topics. In Europe the most outstanding topics of research were on "*Biomedical Implants with Electron Beam Melting and Selective Laser Melting*", "*Mandibular Reconstruction Surgical Planning*" and "*Selective Laser Melting*". More detailed information was generated for each topic[83]. An example is given in Annex 9 for the research front "*Micro-Stereolithography*". The results of the analysis were added to the Sectors-Application Matrix (see Annex 2) as to complement the other outputs of both qualitative and quantitative analyses briefly depicted under Section 3.

83 i.e. research disciplines, keywords, pioneering publications, a list of most recent publications and key scientists with their respective affiliation

Table 10: Distribution of Publications by Research Fronts and Continents (bold: strength of the EU)

Research Fronts	Africa	Asia	EU	Europe (without EU)	North America	Oceania	South America
3D Bioprinting		31	62	7	127	10	1
Additive Manufactured Scaffolds-Based Bone Tissue Engineering	1	106	76	10	53	6	5
Biomedical Implants EBM and SLM	1	37	**177**	10	65	8	3
Guided Surgery Dental Implants		22	96	21	25		17
Mandibular Reconstruction Surgical Planning	6	51	**113**	12	63	9	17
Microstereolithography		71	36	1	69	2	1
Photonic Chrystals Stereolithographie		31	2				
Additive Manufacturing, Misc.	1	14	54	5	24	2	6
Selective Laser Melting	5	150	**229**	17	34	3	
Silicon Purification By Electron Beam Melting		53					3
Ultrasonic Additive Manufacturing		4	6		41		
not assigned	45	1615	2127	243	1729	208	104
Sum	*59*	*2185*	*2978*	*326*	*2230*	*248*	*157*

Source: Web of Science, own calculation

The most active companies are listed for each topic in Table 11[84]. Some selected findings for the three research fronts where Europe is particularly strong can be summarised as follows:

1. Biomedical metallic implants made with materials such as titanium, tantalum, chrome, cobalt and stainless steel have been in routine clinical use for several years. Medical grade Titanium alloys (Ti6Al4V) are widely used as implant materials due to their high strength to weight ratio, corrosion resistance, biocompatibility and osseointegration properties. The porous structures produced by the electron beam melting process present a promising rapid manufacturing process for the direct fabrication of customised titanium implants for enabling personalised medicine.[85] Most active companies in this research field were *3D Syst LayserWise, 3T RPD Ltd.; Avio SpA, Implantcast GmbH* and others, all with addresses in Europe.
2. Mandibular reconstruction is often needed after partial resection and continuity defect. The aims for reconstruction are the maintenance of proper aesthetics and symmetry of the face and the achievement of good functional result, thus preserving the form and the strength of the jaw and allowing future dental rehabilitation. Using Electron Beam Melting or Selective Laser Melting (SLM) is a rapid prototyping method by which porous implants with highly defined external dimensions and internal architecture can be produced. These methods for the processing of titanium have led to a one-step fabrication of porous custom titanium implants with controlled porosity to meet the requirements of the anatomy and functions at the region of implantation.[86] Besides European *IVS Technology GmbH and Mat Dent NV* situated in Switzerland and Denmark most prominent companies were located in USA or China.

84 The analysis of organizations is demanding as the spelling and notation of an organization's name is not unique in the data source. Organizations may have changed their names or organization structures over the considered time span. Mergers and reorganizations of institutes and companies are not documented in the data sources. Therefore the available information of organizations in the specific data field was standardized manually. Even this work proofed to be a challenge. As countries have different institutional structures on universities for instance, as the department is quoted, sometimes a business unit, or the institute, and often it is not possible to decide about the hierarchical role of them. Nevertheless standardization was performed to show the visibility of the organizations. Therefore the reader is asked to take these preceding thoughts into account for considering the analysis of organizations.

85 Mróz W1, Budner B, Syroka R, Niedzielski K, Golański G, Slósarczyk A, Schwarze D, Douglas TE. (2015). In vivo implantation of porous titanium alloy implants coated with magnesium-doped octacalcium phosphate and hydroxyapatite thin films using pulsed laser deposition. J Biomed Mater Res B Appl Biomater. 2015 Jan;103(1):151-8. doi: 10.1002/jbm.b.33170. Epub 2014 May 7. Parthasarathy, J., Starly, B., Raman, S., & Christensen, A. (2010). Mechanical evaluation of porous titanium (Ti6Al4V) structures with electron beam melting (EBM). Journal of the Mechanical Behavior of Biomedical Materials, 3(3), 249-259. doi: http://dx.doi.org/10.1016/j.jmbbm.2009.10.006

86 Cohen, A., Laviv, A., Berman, P., Nashef, R., & Abu-Tair, J. (2009). Mandibular reconstruction using stereolithographic 3-dimensional printing modeling technology. Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology, 108(5), 661-666. doi: http://dx.doi.org/10.1016/j.tripleo.2009.05.023

3. Selective laser melting (SLM) is driven by the need to process near full density objects with mechanical properties comparable to those of bulk materials. During the process the powder particles are completely melted by the laser beam. The resulting high density allows avoiding lengthy post-processing as required with selective laser sintering (SLS) of metal powders[87]. Companies identified in this research fields were *EADS, LayerWise NV, Inspire AG* as well as *Robert Bosch GmbH and Siemens Turbomachinery AB*.

Table 11: Companies by research fronts – Authors' affiliations of type "company", European companies marked in grey

Name of Research Front	Most Active Companies
3D Bioprinting	NanotecMARIN GmbH, D-55128 Mainz, Germany
	Organovo Inc, San Diego, CA 92121 USA
	Stratasys Ltd, Rehovot, Israel
	TeVido BioDevices LLC, Austin, TX 78727 USA
Additive Manufactured Scaffolds-Based Bone Tissue Engineering	Biomatica Srl, Rome, Italy
	Hitachi Ltd, Hitachnaka Ibaraki 3128506, Japan
	Mo Sci Corp, Rolla, MO USA
	ReMeTeks Closed Corp, Moscow, Russia
Additive Manufacturing miscellaneous	Airbus Ltd, Bristol, Avon, England
	EADS Innovat Works Metall Technol & Surface Engn, D-81663 Munich, Germany
	EADS Innovat Works, Bristol BS997AR, Avon, England
Biomedical Implants EBM and SLM	3D Syst LayerWise NV, B-3001 Leuven, Belgium
	3T RPD Ltd, Newbury RG19 6HD, Berks, England
	Avio SpA, I-10040 Turin, Italy
	Ctr Sviluppo Mat SpA, I-00128 Rome, Italy
	Implantcast GmbH, D-21614 Buxtehude, Germany
	LayerWise NV, B-3001 Heverlee, Belgium
	LayerWise NV, B-3001 Leuven, Belgium
	Lima Corp, Milan, Italy
	Simpleware Ltd, Exeter EX4 3PL, Devon, England
	SLM Solut GmbH, D-23556 Lubeck, Germany
	Stanmore Implants Worldwide Ltd, Elstree WD6 3SJ, Herts, England
Mandibular Reconstruction - Surgical Planning	IVS Technol GmbH, Chemnitz, Germany
	Mat Dent NV, Dept Res & Dev, Louvain, Belgium
	Med Modeling Inc, Golden, CO USA
	Mitralign Inc, Tewksbury, MA USA
	Shanghai Dragon Automot Technol Co Ltd, Shanghai 201600, Peoples R China
	Shanghai ZhiZi Automot Co Ltd, Shanghai 201600, Peoples R China
	Siemens Healthcare, Cardiovasc MR R&D, Chicago, IL USA
Microstereolithography	AlpZhi Inc, Atlanta, GA 30318 USA
	Dow Chem Co USA, Elect Mat, Newark, DE 19713 USA
	GE Global Res, Niskayuna, NY 12309 USA
Selective Laser Melting	3DSIM LLC, Louisville, KY 40202 USA
	EADS Innovat Works Metall Technol & Surface Engn, D-81663 Munich, Germany
	Eurocoating Spa, I-38050 Cire Di Pergine, Trento, Italy
	INSPIRE AG Mechatron Prod Syst & Fertigungstech, IRPD, St Gallen, Switzerland
	INSPIRE AG Mechatron Prod Syst & Fertigungstech, Zurich, Switzerland
	Inspire AG, Inst Rapid Prod Dev, St Gallen, Switzerland
	K4Sint Srl, Pergine Valsugana, TN, Italy
	LayerWise NV, B-3001 Heverlee, Belgium
	LayerWise NV, B-3001 Leuven, Belgium
	Panason Corp Eco Solut Co, Kadoma, Osaka 5718686, Japan
	Polaronyx Inc, San Jose, CA 95131 USA
	Robert Bosch GmbH, Schwieberdingen, Germany
	Sichuan Petr Perforating Mat Ltd, Longchang 642177, Peoples R China
	Siemens Turbomachinery AB, S-61231 Finspang, Sweden
	SLM Solut GmbH, D-23556 Lubeck, Germany

[87] Kruth, J. P., Froyen, L., Van Vaerenbergh, J., Mercelis, P., Rombouts, M., & Lauwers, B. (2004). Selective laser melting of iron-based powder. Journal of Materials Processing Technology, 149(1–3), 616-622. doi: http://dx.doi.org/10.1016/j.jmatprotec.2003.11.051

Name of Research Front	Most Active Companies
	▶ Units IM Technol AG, St Gallen, Switzerland
Silicon Purification by Electron Beam Melting	▶ Baotou City Shansheng New Energy Co Ltd, Inner Mongolia, Peoples R China
	▶ Grikin Adv Mat Co Ltd, Beijing, Peoples R China
	▶ Qingdao Longsun Silicon Technol Ltd, R&D Dept, Qingdao 266000, Peoples R China
Ultrasonic Additive Manufacturing	▶ Edison Welding Inst, Columbus, OH 43212 USA
	▶ Solidica Inc, Ann Arbor, MI 48108 USA
Guided Surgery Dental Implants	▶ *No companies were found in the data set analysed*
Photonic Chrystals Stereolithography	▶ *No companies were found in the data set analysed*

Source: Web of Science, own calculation

The outputs of both the desk research and quantitative analyses were used as inputs to the Sectors-Applications Matrix presented below (see Table 23). This matrix available in Annex 2 depicts every technology and associated geographical concentration, components of the European supply chain, the potential of the application area as well as its expected socio-economic impacts. Among the 65 combinations of sectors and AM applications, were for instance satellites' components (e.g. multifunction casing, RF filters, optical baseplate, bracket) or personalized smart medicine. The matrix was kept as open as possible in order to grasp all possible application fields to which AM is bringing or is expected to bring key changes. Both Additive Manufacturing in the industry and consumer 3D-Printing were taken into account (including some areas such as AM for Music instruments).

4/ Case studies: Mapping 10 European Additive Manufacturing Value Chains

4.1 Process, approach and methods

OVERVIEW. Complementary to the desk research and quantitative analyses, 10 AM value chain analyses were to be performed in the form of application-driven case studies. These case studies aimed at:

- Re-constructing the value chain(s) segment by segment by identifying key players (companies, research and technology organisations, clusters etc.) and their activities;
- Identifying missing competencies in the regions considered and opportunities for joint activities between them.

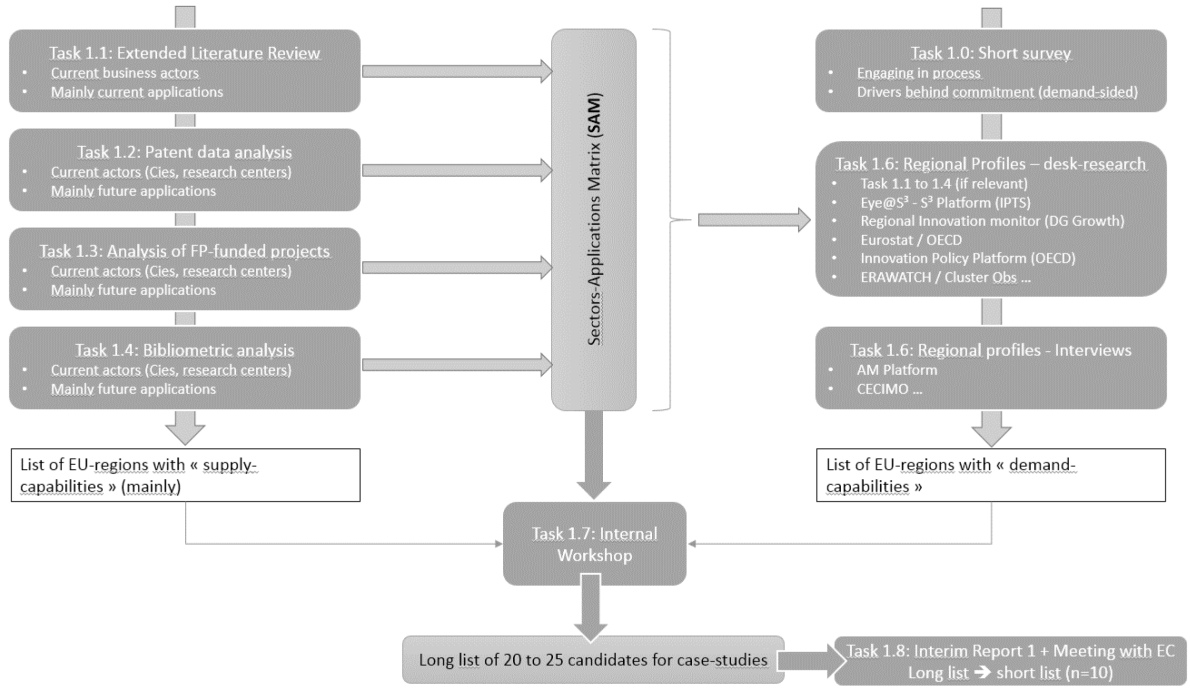
In addition, the research consortium performed an analysis of barriers to the uptake and deployment of AM along each of the selected value chains, as well as a comprehensive listing of relevant policy implications.

Box 8: Barriers and missing capabilities

Barriers were distinguished from missing capabilities. While missing capabilities are economic activities in a specific value chain segment that are either missing or under-developed in Europe, barriers cover a broad range of factors influencing the development of those activities whether they are located in Europe or not. Barriers can include the lack of knowledge, economic factors, social factors, and other variables that influence the level of adoption and deployment of a technology in a given system. Although missing capabilities can sometimes be barriers themselves, they were in this study dissociated from barriers for the sake of clarity. Moreover, it is not because a capacity is missing or under-developed that the adoption and deployment of AM will be hampered. It can however mean that European players and their use of AM might to some extent depend on foreign entities.

The all process of identification and selection of the 10 relevant value chains is presented in Figure 6. Parallel to Tasks 1.1, 1.2, 1.3 and 1.4 which aimed at shaping up the Sectors-Application Matrix, Task 1.6 consisted in the profiling and classification of the regions. All inputs fed in Task 1.7 where decisions were taken over the selection of the final application areas to be researched in depth.

Figure 6: Detailed approach to the selection of the value chains



SELECTION OF THE CASES. The first phase of the project led to the identification of the most important future applications in 3D-Printing[88], considering the applications at post-prototyping level (> TRL5) with a potential market deployment within the 3 to 5 years. 65 applications were identified and ranked according to their technological maturity and market potential (see Annex 2Deel 12/). 10 application areas were to be selected out of this list. In order to operate the selection, three main tasks were performed:

1. **First**, a first profiling of the regions was performed in order to position each region regarding thematic areas (such as "healthcare", "automotive", "advanced manufacturing technologies", etc.).

Box 9: Drafting and positioning regional profiles

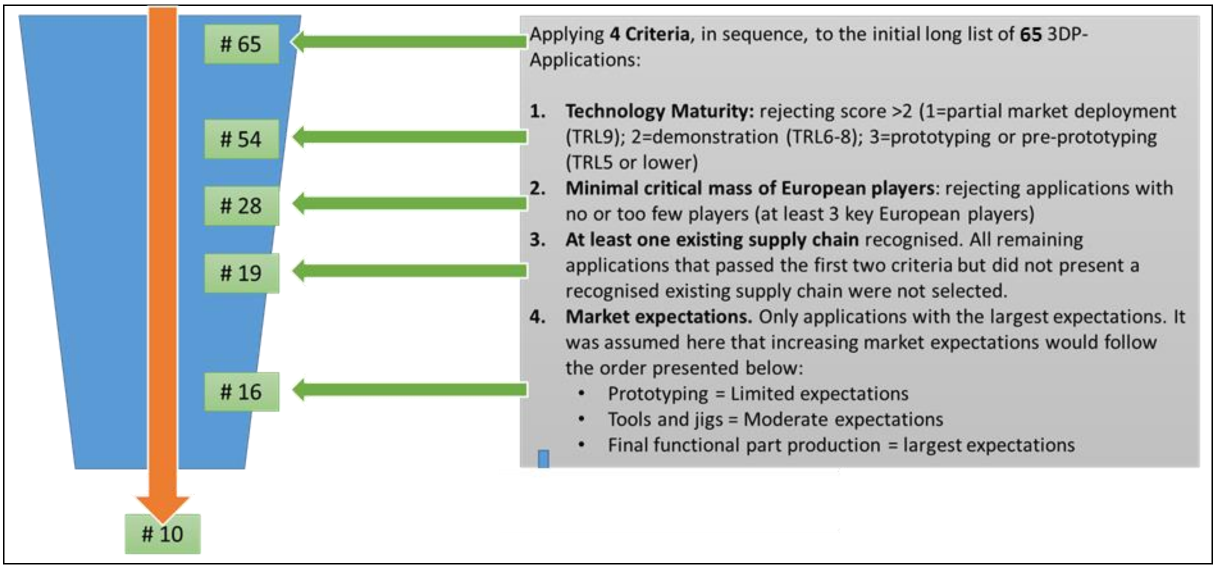
Parallel to the identification of the applications through the desk research and quantitative analyses, a profile was constituted for 70 regions in order to identify the main economic specialisation areas and connect these to specific applications. Geographical balance was targeted at the level of the EU28. A balance between lead and less advanced regions was also sought. AM supply capabilities and (current or potential) demand could be identified following an analytical grid and positioning the regions in function of key sectors[89], themes and criteria. 4 main aspects were investigated: **1)** the regional structure (dominant sectors, etc.); **2)** the existence of AM capabilities (presence of AM providers, etc.); **3)** the development targets and strategic orientations of each region (either towards AM, AMT or specific applications); and **4)** the regional specialisation pattern(s) at play. Several sources were used such as the Smart Specialisation Platform or the "Eye@S³ Tool" of the IPTS[90], the Regional Innovation Monitor Plus[91], etc. A classification table was produced to cluster and rank the regions in view of the upcoming case selection workshop. A more detailed view on the process and resulting clusters is available in the Section 4.1 of the Background Report.

2. **Second**, a workshop[92] was organized in order for the experts involved to make the selection of the 10 most relevant application areas and finalize the association of regions to those according to their profile characteristics. This workshop led to the final version of the SAM as well as to a prioritized list of applications including the 16 long-list of application areas potentially relevant to the case study research to be performed.

Box 10: Selecting application areas and associating regions to these areas

Following a discussion on the scope of the sector-application areas, the participants to the workshop (from both the consortium and external organisations) performed a prioritisation exercise to link the application areas to regions. Criteria were used to select the application areas: technology maturity (only close-to-market applications were retained, leading to a list of 54 area); the presence of a minimum critical mass of EU players (28 regions remained); the existence of at least one supply chain (19 areas remained after this criterion was applied); and the market expectations (leading to a final long-list of 16 application areas). The second part of the workshop was dedicated to the allocation of regions to each of the 16 application areas depending on their individual profile. A set of three criteria (see below) was used in that respect[93]. Each criterion was used as a filter: every application area that would not match the expectations of a filter would be dropped from the selection. Therefore, the selection of applications followed four "filtering" rounds.

[88] As agreed before we consider 'Additive Manufacturing' (AM) and '3D-Printing' (3DP) as synonyms.
[89] Each of the regions was for instance positioned in function of a set of 40 main economic sectors.
[90] See http://s3platform.jrc.ec.europa.eu/home and http://s3platform.jrc.ec.europa.eu/map
[91] See https://ec.europa.eu/growth/tools-databases/regional-innovation-monitor/
[92] The workshop aimed at: Selecting the most relevant 3DP applications to consider for the case studies; Allocating regions to these application areas; Validating the resulting combinations as cases to be further investigated during the next steps of the project; and establishing a long list of cases from which ten case-studies will be finally selected.
[93] The criteria used for the allocation were 1) the presence of a relevant industrial activity in the field (or in a related field); the existence of a minimum critical mass, assessed through the presence of key (significant) industrial players in the region (either as supplier of 3DP applications (technology developer) or as potential lead-user); and the possibility for the region to take a leading role in terms of the segments of the value chain missing (upward/downward segments).



Using the aforementioned criteria (see Box 10), we prioritised the applications and selected 16 key 3DP-applications for further research. Following up on the workshop, the research consortium in close collaboration with the European Commission selected a short-list of **10 applications**. The following application areas were selected as a basis for each case study to be performed[94]:

1. Surgical planning
2. Plastic-based car interior components
3. Metallic structural parts for airplane
4. Inert and hard implants
5. Metal AM for injection Molding
6. Spare parts for machines
7. Lighting and other home decoration products
8. 3D-printed textiles
9. Affordable houses
10. 3D-printed confectionery

CASE STUDY PROCESS. The case studies took place in two phases. **First** the scope of the application area was to be refined and key players and value chain components were to be identified for each cases. **Second** critical factors, barriers to the uptake and deployment of AM as well as policy implications were to be derived from the available evidence and resulting analysis. Each of the phases was started with a pilot round. A case study protocol guided the all case study process, setting up the frame for the iterative rounds of desk research and 124 semi-structured interviews (listed in Annex 14) and written feedbacks from gate keepers and representatives from the supply and (potential) demand sides of the AM value chains. Interviews first targeted "*gate keepers*" (experts, cluster managers, etc.) and then (potential) users and suppliers of AM technologies and services. Several meetings internal to the consortium were organized in order for the research team to exchange on specific and cross-case insights.

[94] The final list involved an evidence-based selection of 10 key applications from the previous 16 application areas which were refined in collaboration with the services of the European Commission. Only the areas relevant to the study were retained. For example, the application areas "*structural components for cars*" and "*structural components for aircrafts*" from the list of 16 application areas were merged into one; when refining the case study unit with the relevant selection criteria, it appeared that only non-engine metallic structural components of aircrafts were to be considered as they were 1) in the contrary of automotive structural components, mature enough and close to commercialization, 2) not yet fully deployed to the market (while plastic-based and non-structural components are already deployed) and 3) most likely to constitute an area to which AM can bring value due to the more restrictive number of outputs (in terms of production series) issued from the sector.

Box 11: Scope of the AM application-driven case studies

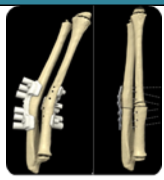
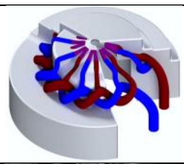
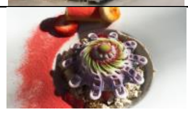
The case study research was oriented towards main investigation topics derived from the research questions that guided this study. As a result, each case study investigated for each selected value chain:

1. The context of AM in the broad sector in which the application is being in use;
2. A refined scope for each AM application area;
3. The identification of AM key players and value chain segments;
4. The analysis of critical factors and regional AM (missing) capabilities;
5. The analysis of barriers to the uptake and deployment of AM as well as related policy implications.

RESULTS. After the selection of the **10 AM application-driven value chains** to be further investigated, each case study was conducted by using a combination of desk research and semi-structured interviews. The case study process was framed by the use of a case study protocol depicting every aspect of the process, topics to be discussed, analysis and reporting modalities. The value chain analyses were completed by an identification of barriers to the uptake and deployment of Additive Manufacturing together with related policy implications.

4.2 Overview of the 10 selected AM Value Chains

The following sub-section presents an overview of each of the value chain analyses performed in the form of application-driven case studies. These are synthetic version of the full case study reports available in Section 4 of the Background report. Cross-case insights will then be presented as well as key implications in the Conclusion section (see 5/).

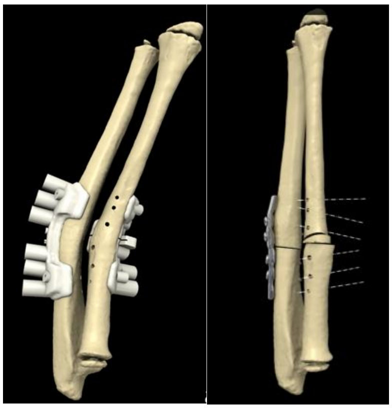
Section	Case Study
0	**Surgical Planning** 
4.2.2	**Plastic-based car interior components** 
4.2.3	**Metallic structural parts for airplane** 
4.2.4	**Inert and hard implants** 
4.2.5	**Metal AM for injection molding** 
4.2.6	**Spare parts for machines** 
0	**Lighting and other home decoration products** 
4.2.8	**3D-printed textiles** 
4.2.9	**Affordable houses** 
4.2.10	**3D-printed confectionery** 

4.2.1 Surgical planning

CONTEXT. Since the adoption of AM by the sector in the 2000s, the use and quality of AM applications in healthcare increased[95] and it is now expected to lead to a revolution (Ventola, 2014)[96]. It is a large market with value-dense products of limited sizes (compared to aircraft components), and a lot of potential is foreseen in customization[97]. With a total market of about $490 million, AM in healthcare is expected to grow to $2,13 billion in 2020[98]. Although various applications[99] from different categories[100] benefit from AM in healthcare, this case study was focused on "*Models for preoperative planning, education and training*" and "*Tools, instruments and parts for medical devices*" grouped together under Surgical Planning[101]. A total of $644 million in value of printed components alone originating from surgical planning is expected by 2020[102]. It is expected to benefit the patient, surgeons and hospitals[103,104] thanks to customized and to some extent more accurate tools that can be produced cost-effectively.

SCOPE. Surgical planning consists in 3D-printed surgical guides used to transfer a virtual surgical plan to real life. A surgical guide is a union of two components: the guiding cylinders or oblique holes and the contact surface[105]. A 3D-printed medical model is a model of a body part (e.g. organs, limbs, spine, and teeth) which is produced via additive manufacturing. It is not used inside the body. Surgical and drilling guides (see Figure 7) are currently key additive manufacturing applications[106] and have a growing market expectation.

Figure 7: from left to right, (a) Drilling and cutting guide design based on initial anatomy and planned outcome (b) Illustration of patients-specific plates with pegs which follows the contours of the bone.



Source: Video on patient-specific guides and plates for a double forearm malunion case[107]

It is also observed that companies often provide services for surgical planning including the 3D-printed tools and instruments as well as the 3D-printed medical models, where also the main market opportunities occur[108].

95 Gross BC, Erkal JL, Lockwood SY, et al. Evaluation of 3D-printing and its potential impact on biotechnology and the chemical sciences. Anal Chem. 2014;86(7):3240–3253.

96 Ventola, C. L. (2014). Medical Applications for 3D-printing: Current and Projected Uses. *Pharmacy and Therapeutics*, *39*(10), 704–711.

97 3D opportunity in medical technology: additive manufacturing comes to life. Deloitte University Press.

98 http://www.fabulous.com.co/blog/2015/11/impression-3d-medecine-medical-sante-quel-marche/

99 Such as Models for preoperative planning, education and training; Medical aids, supportive guides, splints, and prostheses; Tools, instruments and parts for medical devices; Inert implants; Bio manufacturing (tissue engineering and additive manufacturing).

100 Tuomi J, Paloheimo K, Björkstrand R, et al. Medical applications of rapid prototyping – from applications to classification. In: da Silva Bartolo PJ, Jorge MA, de Conceicao Batista F, et al. (eds). Innovation development in design and manufacturing: advanced research in virtual and rapid prototyping – Proceedings of VR@P4, Leiria, Protugal, October 2009, pp. 701-704. Boca Raton, FL: CRC press.

101 In addition, the literature often combines 3D-printed surgical guides and tools and 3D-printed anatomic medical models and labels them together as "surgical planning".

102 Opportunities for additive manufacturing in surgical planning and modelling http://www.researchandmarkets.com/reports/3388719/

103 EOS- Additive manufacturing in the medical field. https://scrivito-public-cdn.s3-eu-west-1.amazonaws.com/eos/public/b674141e654eb94c/c5240ec3f487106801eb6963b578f75e/medicalbrochure.pdf

104 Additive manufacturing workshop Medtech 2015: presurgical planning in hospitals supported by additive manufacturing

105 Ramasamy M, Giri, Raja R, Subramonian, Karthik, Narendrakumar R. Implant surgical guides: From the past to the present. *Journal of Pharmacy & Bioallied Sciences*. 2013;5(Suppl 1):S98-S102. doi:10.4103/0975-7406.113306.

106 3D opportunity in medical technology: additive manufacturing comes to life. Presentation by Dr. Mark J. Cotteleer, 22 April 2015.

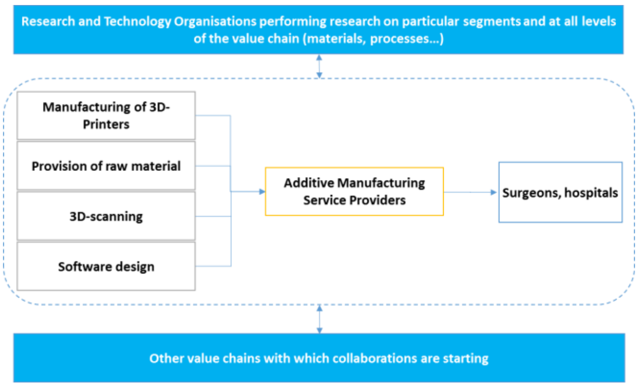
107 http://ortho.materialise.com/cases/patient-specific-guides-and-plates-double-forearm-malunion-case

108 Opportunities for additive manufacturing in surgical planning and modelling http://www.researchandmarkets.com/reports/3388719/

The market for personalized 3D-printed surgical guides and tools can mainly be seen as 1) cutting guides (surgical guides to temporary put over the bone, inside the body), 2) drilling guides (temporary put over the bone, inside the body)[109] to indicate where the surgeons should either cut or drill; and 3) other tools and instruments (such as customized scalpels, etc.). Guides allow for[110] precisely transferring virtual planning into the surgical environment, reducing operating time and improving precision. Their use implies that they are made of biocompatible materials. Models for preoperative planning, education and training (medical models) are often made of polymers but also steel and rubber. They can be used for surgical preparation, training and education, but also communication to the patient. Models for preoperative planning, education and training (medical models), anatomical models appear to be mainly used to prepare surgery[111]. A broad range of specific products could be identified, from brain or spine surgery tools to drilling guides. they have in common the need for precision, reliability and of course biocompatibility.

VALUE CHAIN. When considering the two segments falling under the scope (tools and instruments for surgery and 3D-printed models), one can notice the presence of large US-based AM providers (Stratasys, 3D Systems [incl. its Belgium branch Layerwise]) but also European companies (EnvisionTEC [DE], Arcam [SE], Materialise [BE]). These companies spread along the value chain, from software design to the use of techniques such as Laser Sintering of metal powders to produce tools or molds to make those tools. Manufacturing of 3D-Printers is an activity that can either be found in American firms or in Western European ones such as Belgium, Germany, British or Swedish companies. The materials (mainly metals and polymers for guides, a broader range of materials for models), 3D-scanning and software capabilities are provided by a broad range of companies: specialized software are needed which are mostly available from Belgium, French, German and US companies. Large players such as Johnson and Johnson (US), Stryker (US), Zimmer Biomed (CH), Smith and Nephews (US) and Siemens healthcare (DE) developed some AM capabilities to complement their subtractive techniques in the making of surgical guides[112]. Materialise (BE), Renishaw (UK), Stratasys (IL), Xilloc (Nl) and Oxford Performance materials (UK) are suppliers of AM printers and services who developped a business line on healthcare. Key consumers in the value chain remain hospitals (and in particular surgeons).

Figure 8: Main segments of the surgical planning additive manufacturing value chain



3D-printed models are increasingly in use for training purposes, but awareness is still lacking among the user community. From the side of Research and Technology Organisations (RTOs), developments are taking place in collaboration with the private sector on topics such as multi-and biodegradable materials. Connections with other value chains are limited except for other health-related value chains. However, links are observed between (mainly Western European) regions as key players collaborate accross Europe. Flanders and Wallonia regions (BE) provide good examples of such players from the service provision side (KUL, Melotte, Layerwise, Materialise, Mobelife NV, etc.) while Bavaria and Baden-Württemberg in Germany concentrate the metal AM printers provision players (such as EOS, SLM-Solutions, ConceptLaser, etc.). Other regions play a role, such as Emilia-Romagna (IT) and Asturias (ES) where developments can be observed. The rise of AM for surgical planning might lead to changes in the value chain: in particular "*manufacturing closer to the point of use*" is seen as an upcoming application as hospitals might be able to print their own models in the near future. They could possibly do so not even buying a printer but going for a leasing option.

BARRIERS AND POLICY IMPLICATIONS. The uptake and deployment of AM remain limited by the lack of training and appropriate skills (CAD, management, manufacturing, etc.). These should be oriented toward a multi-disciplinary approach calling upon different fields (engineering, health sciences, etc.). Despite of the current hype, the use of AM for surgical planning is not well-known across the user community. Moreover, printers remain expensive for hospitals to buy, and often do not match expectations of the surgeons in terms of precision and reproduction of surgery conditions. AM for surgical planning might also be threatened by the rise of virtual reality technologies allowing for virtual planning. Currently, a lot of the efforst in healthcare with respect surgical planning is still focused on hard tissue such as maxillofacial reconstruction and orthopaedic applications. The majority of the body consist of soft tissue though, which requires more elastic properties of the material. A main missing capability in surgical planning is the availability of surgical models consisting of elastomeric type of materials (polymer) which

[109] Opportunities for additive manufacturing in surgical planning and modelling http://www.researchandmarkets.com/reports/3388719/

[110] Naghieh, Saman, Badrossamay, M. and Foroozmehr, E. Frabriation of cutting guides for Oral and maxillofacial bones by additive manufacturing techniques: case studies. Presentation at 3rd congress of Iranian oral and maxillofacial pathologist 29-31 July 2015, Iran-Isfahan

[111] Ventola, 2014

[112] Other companies are Encoris (Nl), 3D-side (BE), Lima Corporate (It), etc.

have these elastic properties. Very important for these models is their fidelity. The availability of these models focussing on soft body tissues such as cardiovascular and gastrointestinal models, would allow for high fidelity training to de-risk training new practicioners. Other missing capabilities are the multidisciplinary skills (related to surgery, radiology and engineering). Overall, Europe also lags behind the US with respect to the implementation of the technology itself into service design. It is also concerned with missing and/or under-developped capabilities such as presented in Box 12. The possible development of the use of AM for surgical planning would not impact the structure of the market as liability would still be a more determinant factor compared to others such as IPR.

Box 12: Missing and/or under-developed capabilities in this value chain include...

- Materials capabilities (not only hard materials but also soft tissues, etc.);
- Capabilities are mainly concentrated in Western European regions;
- The software segment should further be developed.

Therefore, a series of poliy implications were derived from the case study, seen as the needs to:

1. Improve skills and training availability in strategic areas such as CAD, materials, management, etc. [113]. This should at least be implemented at the national level as education and training programmes need to be developed. The diversification of the training and education offered will benefit from a coordinated EU-approach.
2. Support multidisciplinary collaboration in order to stimulate the development of multidisciplinary skills. Project-based initiatives can initiate a first collaboration between e.g. engineers and surgeons/clinicians. Incentives at local, national, and EU level are necessary
3. Support R&D in the field to overcome technical barriers. Technical barriers (price of printers and materials, accuracy and fidelity of the tools) still exist at all steps of the value chain. R&D support in the form of EU, national and regional funding programmes can help to overcome these technical barriers.
4. Co-invest in the acquisition of printers to reduce the cost for adopters (hospitals) via regional and national initiatives.

   Promote information sharing between healthcare professionals, healthcare companies and AM suppliers.At all levels (EU, national and regional level) it is important to rise awareness among the user community.
5. There is still a lot of diversity between the different countries with respect to the payment of models and surgical tools. A more coordintated approach at the EU-level will certainly benefit the uptake of AM in healthcare.

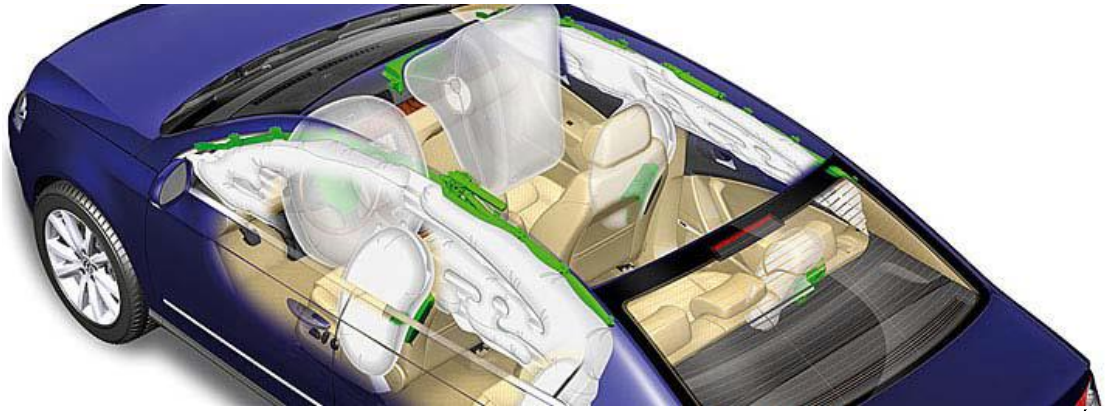
4.2.2 Plastic-based car interior components

CONTEXT. AM in the automotive industry is now expected to reach a combined production volume associated to the generation of $1.1 billion revenue by 2019 (Royal Academy of Engineering, 2013) and could bring a revolution to the sector[114]. 100 000 prototype parts and molds are already 3D-printed every year andthe revenue generated by the sale of 3D-printers to the automotive industry should reach $586 million, while materials revenues would reach $376 million by 2019[115]. The use of AM remained however focused on prototyping, although some operational uses can be found on certain segments such as the one of Formula 1[116].

SCOPE. AM in automotive is concerned with both structural and non-structural components. Although developments take place at the level of structural components, AM was mainly used to print car interior and exterior parts. Car exterior is however less subject to AM. With about 250 parts on average, car interior (see Figure 9) comprises interior carpets, rugs and floor kits and (dash) mats, upholstery (seats including cushions and chairs), headliners and floor liners, convertible tops and vinyl roof covers, as well as dashboards; among these, about 90 parts are made of plastic material (Szeteiová, 2010)[117].

[113] 3D opportunity in medical technology: additive manufacturing comes to life. Deloitte University Press, 2014.
[114] See http://www.autocar.co.uk/car-news/motor-shows-detroit-motor-show/how-3d-printing-could-revolutionise-car-industry
[115] See http://smartechpublishing.com/news/smartech-publishing-announces-automotive-industry-producing-record-volumes
[116] The company would mainly call upon SLS and FDM
[117] Decoration items such as trims are not included in this classification.

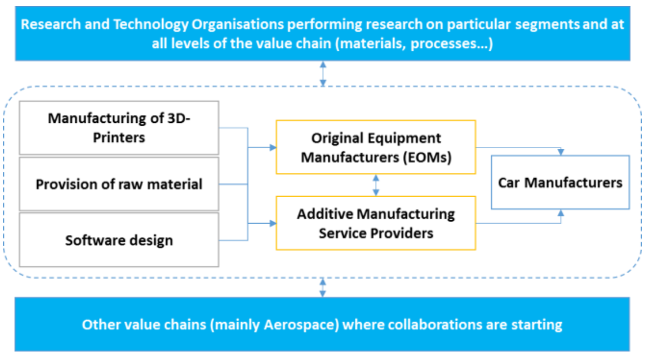
Figure 9: Interior of a typical vehicle



Source: Szeteiová (2010)

Although some items can be printed with metal (such as in the case of the Bloodhound[118] vehicle's steering wheel), one can note that plastics[119] are also mostly used to print components that are part of the cockpit or cabin. Window frames and dashboard components are particularly relevant to the use of AM and it appears from the evidence gathered that the main development tracks concern plastic-based AM and that the proportion of plastics used in the making of a car is increasing[120]. AM service providers such as Materialise (BE) collaborate with car manufacturers such as Peugeot to develop new perspectives (see for instance the anechoic components of the Peugeot Fractal prototype of which 82% of the cockpit was 3D-printed[121]).

Figure 10: Main segments of the car interior additive manufacturing value chain



VALUE CHAIN. The raw materials market is rather international and fragmented (with a broader range of powder[122] suppliers); large players can however be identified such as DSM and its SOMOS branch (NL), Evonik (BE) and Arkema (FR). The software segment is dominated by incumbents (also regarding CAD) such as Dassault (FR), Siemens (DE) or Materialise (BE) who dominates the field of interface software. Despite of the competition coming from Japan and US-based firms (such as Ford, General Motors[123] but also AM services and printers providers like Stratasys), Europe developped some capabilities in regions where main car manufacturers are active. Printer manufacturers such as EOS (DE), ConceptLaser (DE), Oxojet (DE) and SLM Solutions[124] (DE) are facing international competition from 3D Systems (US), Stratasys (IL), InJet (US), Matsuura and SOUP (JP), but also RICO (US) and HP (US). These firms provide car manufacturers such as (PSA and Renault [FR], BMW and Volkswagen [DE], etc.[125]) but also OEMs (Tenecco, Boysen, Faurecia, Edag, Eberspaecher, IAC, Johnson Controls Inc., YANFENG and Valeo) with devices and expertise to develop their internal AM capabilities.

118 See http://www.bloodhoundssc.com/
119 See http://www.plastics.gl/automotive/styrenic-polymers-in-automotive-interior-and-exterior/
120 See Szeteiová, 2010
121 See http://www.peugeot.com/en/news/fractal-amplifies-the-peugeot-i-cockpit-with-sound
122 Mostly Powder-based solutions are being used in the field, although fused deposition modelling and other techniques are also mobilised.
123 See http://www.adandp.media/articles/rapid-prototyping-how-its-done-at-gm
124 And for information, for non-plastic components mainly ConceptLaser and Trumpf.
125 Uses could be identified in BMW, Koenigsegg, Peugeot, Renault, Volkswagen, Audi, Porsche, Daimler, KIA, Lamborghini, Ferrari, Fiat, Volvo, Maserati and their American and Japanese counterparts (Ford, Honda and in particular on additive manufacturing General Motors).

Almost all capabilities underlying this value chain can be found in Europe; only the CAD and engineering software segment could be strengthened (see Box 13) as it is subject to a high level of international competition. One can note that most capabilities are being developed in Western European regions[126] and in particular German regions where both automotive and AM capabilities are strong. They still focus on protyping, tooling and to a limited extent to short series production. Parts and assembly verifications are also under the scope. Development still takes place in this area as universities and research centres[127] collaborate with the private sector on the topic. Knowledge transfers are therefore facilitated, also across value chains as collaborations are being set up between the aeronautic and automotive sectors. Among the few collaboration initiatives identified, the Vanguard Initiative[128] is currently supporting several joint demonstration projects oriented towards the automotive sector. They are now mainly concerned with qualification and standardization, as well as with technical issues such as the efficiency and productivity of AM. Many trends are foreseen such as the printing of large parts, design verification and engine components[129]. Upcoming trends mainly encompass hybrid and multi-material printing but also the emergence of new business models such as the one of LocalMotors (US) who can print a car in 44 hours[130] or Korecologic who develop a green car mainly printed by Stratasys (IL)[131]. More speculative trends can be mentioned such as the installation of 3D-printers at car dealership to produce spare parts[132].

Box 13: Missing and/or under-developed capabilities in this value chain include...

- The CAD software segment could be strengthened further;
- Capabilities are mainly (if not exclusively) concentrated in Western European regions.

BARRIERS AND POLICY IMPLICATIONS. The deployment of AM along this very specific value chain is constrained by the limited performance of the technology: AM does not allow for scale economies and the printing of large parts. Technology efficiency is nonetheless a key driver of this value chain. 3D-printed parts remain expensive when coming to large-scale production and the automation of AM processes is therefore a challenge in that respect. Moreover, post-processing is required to clean up the parts as the quality of their surface is not sufficiently good when issued from AM printers. Their durability is also not optimal. Above all, interviewees flagged the need for more efforts to qualify AM materials and processes as well as appropriate design rules. Together with the further development of the knowledge and technology under the scope, the development of appropriate curricula and skilled workforce comes as a priority for this value chain. Last barriers are found in the risk-aversion and manufacuting conservatism of company and technology managers not used to take advantage of additive processes. These are to be related to design-related IPR and copyrights which are also seen as a barrier (industry players fear that designs could be stolen and parts could be reproduced). Among other trends, the sector is now turning to the printing of leightweight and complex parts but also the development of composite materials and hybrid manufacturing methods. Multi-material and multi-colour printing is of particular importance to car interior parts which are visible to car users who are directly in touch with them. In the longer-run, some expect that full-car printing and mass customization take place. Policy implications can be derived from such analysis of the barriers and trends to AM deployment across the segments of this value chain.

1. First, public co-funding in R&D should support the qualification of AM[133]. New research areas (hybrid manufacturing, composite materials, large parts printing, etc.) require such support which could take place at all government levels through collaborative R&D projects and networked infrastructures.
2. Directly linked to the above is the need for co-investment in AM devices and services, for exemple through adapted taxation schemes (or credits) or other financial incentives but also innovation vouchers.
3. Efforts should also be made to raise awareness and stimulate the demand for AM in the sector by diffusing information on pros and cons of AM to relevant managers (both corporate and technical ones). A one-stop website initiated by the European Commission in that respect (even if it would be externalised afterward) could be an option, together with targeted events.
4. Demand for AM could be stimulated by tools and instruments such as regulation (which impacts the demand for optimized products, e.g. cars with lower rates of CO_2 emission).

[126] Flanders, Wallonia, Rhône-Alpes, Ile-de-France, Auvergne, Piemonte, Lombardy, Emilia Romagna, Ängelholm, Västergötland, Bohuslän, Catalonia, Schleswig-Holstein, Bavaria, Hesse, Hamburg, Low Saxony and Baden Württemberg.

[127] Universities of Milan, Bologna, Salerno, and Padua; the Fraunhofer University, Aachen University, the University of Düsseldorf, the University of Hamburg, and the Zentrum Hannover.

[128] See http://www.s3vanguardinitiative.eu/cooperations/high-performance-production-through-3d-printing

[129] Source : http://3dprint.com/72358/automotive-bn-dollar-market/

[130] Source: http://wardsauto.com/plants-production/your-car-built-you-while-you-wait

[131] See http://korecologic.com/

[132] See for instance http://wardsauto.com/dealers/3d-printing-will-change-auto-industry-manufacturers-dealers?page=2

[133] Although the use of AM is in this value chain limited to prototyping, there is a lot of interest from designers to bring the technology to a new level.

5. IPR enforcement could benefir from an upgrade of IP instances' information capabilities (the EPO and/or IPO could for instance be informed by a dedicated observatory to watch over new designs[134]).
6. Last but not least, skills and curricula should be developed. The EU could initiate a collaborative process as to mobilise relevant communities in that respect.

4.2.3 Metallic structural parts for airplane

CONTEXT. Aerospace is a leading sector that spurs the development of AM[135] in the search for optimization. Non-structural components[136,137] for the interior of the aircraft, jet engine components[138] and structural parts are currently being printed with AM. AM is therefore relatively mature[139] in aerospace. AM applications range from stator rings to fuel injectors (Wimpenny, 2013). AM is also now being explored for activities such as repairing (Allen, 2011) or Maintenance, Repair and Overhaul (MRO) in general. Besides tooling, AM is used for the production of air parts that are currently flying but the constraints due to regulation and certification make the deployment of AM relatively slow, also as the sector is driven by long-term planning with a usual 50-year perspective.

SCOPE. Well-known applications in 2012 were for instance turbine blades, physical 3D mock-ups, structured parts for unmanned aircrafts, customized interiors for business jets & private helicopters, swirlers / fuel injectors, etc.[140] Given the scope of the study, the focus was placed on parts that are structural but close-to-market (not yet developed on the market). Among the structural applications that are subject to AM, engine components appear to have reached a second step in market diffusion. OEMs such as General Electrics (US), Rolls-Royce (UK) [141] and Pratt & Whitney (US) are particularly known for their use of AM for engine components such as fuel nozzles[142,143,144] and are among world-wide leaders in the field. Among other reasons, they make use of AM to make savings on expensive materials such as titanium. The segment of AM for engine components was however too mature to fall under the scope of this case study. The area that was the most relevant was the one of structural parts made with metal AM. This area is concerned with "*large metallic structures*" (Ely, 2015) such as aircraft wings and fuselage but also smaller parts such as brackets[145] (see Figure 11) and less critical components (empennage, etc.). Iron, steel and super-alloys are mainly used for such components which can be printed with a broad range of technologies, from powder-bed to wire-based systems[146] (see Ding et Al., 2014) .

Figure 11: AM bionic titanium bracket for the A350 XWB

Source (from left to right): *http://www.a350xwb.com/photo-gallery/* and *http://www.airbus.com/presscentre/pressreleases/press-release-detail/detail/printing-the-future-airbus-expands-its-applications-of-the-revolutionary-additive-layer-manufacturi/*

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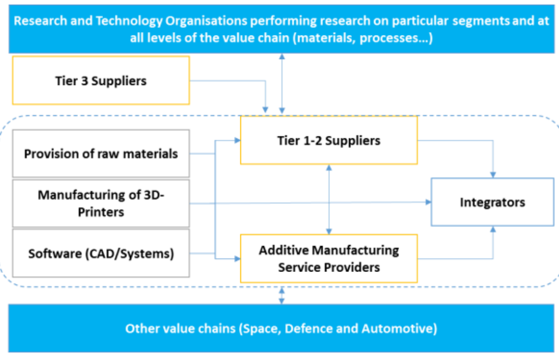
134 Examples are provided in http://www.tandfonline.com/doi/abs/10.5437/08956308X5705256 and on http://ubiquity.acm.org/article.cfm?id=1008537
135 Both industries are indeed early adopters of Additive Manufacturing, in order for instance to speed up prototyping activities.
136 See for instance http://www.stratasys.com/industries/aerospace/airbus
137 See: http://www.theengineer.co.uk/aerospace-takes-to-additive-manufacturing/)
138 See http://www.forbes.com/sites/timworstall/2013/12/02/both-ge-and-rolls-royce-are-to-use-3d-printing-to-make-jet-engines-by-violating-enginererings-prime-commandment/#60dde5f968e1
139 See Roland Berger, 2015
140 See Somasekharappa, 2012
141 See for instance their involvement in the AMAZE project supported by the EC (www.amaze-project.eu/ *and* http://www.reuters.com/article/norsk-titanium-as-idUSnBw035840a+100+BSW20151203)
142 Source : http://www.gereports.com/post/116402870270/the-faa-cleared-the-first-3d-printed-part-to-fly/
143 Source: http://3dprintingindustry.com/2015/02/19/rolls-royce-to-fly-largest-3d-printed-part-ever-flown/
144 Source : http://www.gereports.com/post/119370423770/jet-engines-with-3d-printed-parts-power-next-gen/
145 See http://www.eos.info/eos_airbusgroupinnovationteam_aerospace_sustainability_study
146 In this report, the notion of AM system refers to a set of components and techniques that physically print while the notion of process refers to the steps of manufacturing layer by layer with one or the other technology.

VALUE CHAIN. This value chain is marked by a very high level of concentration around key OEMs, AM suppliers and integrators such as Airbus (FR) or Boeing (US). The key players in this area can therefore be identified quite easily (see for instance Defense IQ, 2016[147]). There is a clear concentration of the aeronautic AM segments in Western Europe and in particular in France, Germany, Italy, and the United Kingdom. The main players on the segment of printer manufacturers are located in Germany[148] while the key aeronautic players in demand of AM technologies and services are either located in France, the UK or Germany[149]. Even American players (GE, Boeing, Lockheed Martin) are active in Europe through their branches in Italy, Northern Ireland, and the UK. Players such as SAFRAN (FR), Boeing (US) and AvioAero (branch of GE in IT), etc. are working with European companies such as EOS, Altair, Techspace Aerospace, MTU Aero Engines (DE)[150], ARCAM AB (SE) and Harcotera (ES) to assimilate and develop AM capabilities. US-based firms such as Stratasys also collaborate with European integrators like Airbus. In Europe, most segments are found in Western European regions. France, Germany, Italy, and the United Kingdom are the countries where capabilities are concentrated. The main players on the segment of printer manufacturers are located in Germany[151] while the key aeronautic players in demand of AM technologies and services are either located in France, the UK or Germany. Also Spain and UK-based players now rising thanks to the demonstration of wire-based systems. Although all capabilities seem to be found in Europe, interviewees pointed at a serious lack of capabilities in terms of powder supply, and in particular in the fields of aluminum and titanium (fields in which China dominates the world-wide market, followed by India and North America). One of the particularities of the aeronautic AM value chain is that integrators and OEMs on a Tier 1 supply level seem to be moving along the value chain. This is the case for example for some OEMs dealing with raw materials such as GKN through Hoeganaes[152] or Airbus with its Scarmalloy[153] for structural applications. Another example is GE that absorbed two AM companies in 2013 – Morris Technologies and Rapid Quality Manufacturing (RQM)[154]). Different business models can be found, either leading to a concentration of AM capabilities under a same roof or to a distribution of capabilities across an eco-system that is formed around one (or more) OEM(s) or integrator(s).

Figure 12: Main segments of the aircraft structural parts additive manufacturing value chain



In terms of missing and/or under-developed capabilities (which are listed in Box 14), several interviewees referred to post-processing and in particular "*Hot isostatic pressing*" as being a missing segment. Specific to wire-based technologies are also the absence of software and system commercially available. In addition, the availability of materials (whether powder or wire-based) is also an issue as it is controlled by foreign entities. When taking the example of powders, one can note that many companies can deliver classical metal powders[155]. When coming to aluminum, the number of key players is more restrictive[156]. This is also the case for titanium.

Box 14: Missing and/or under-developed capabilities in this value chain include...

- Transformative capabilities to turn high-end materials such as titanium and alluminum into powders are missing in Europe;
- CAD capabilities should be further developed;
- Non-Destructive Testing (NDT) and broader testing capabilities;
- Post-processing (including finishing) capabilities should be further strengthened;
- Capabilities are concentrated in Western European regions;
- Wire-based AM systems and appropriate software capabilities are currently missing in Europe;
- Hot Isostatic Pressing (HIP).

147 Survey implemented by Defense IQ and targeting 126 industry professionals.
148 Västergötland (SE), Staffordshire (UK), Schleswig-Holstein, and Bavaria (DE) for instance when coming to powder-based technologies; as well as Cataluña and Bedfordshire regarding wire-based systems.
149 Major integrators and OEMs are for instance present in Midi-Pyrénées, Piemonte, Bavaria, Northern Ireland, Rhône Alpes and Ile-de-France but also Masovian Voivodeship in Poland which stands as an exception.
150 See http://3dprintingindustry.com/2014/08/11/3d-printing-ge-jet-engine/
151 Powder-based printer manufacturers are mainly located in Västergötland in Sweden, Staffordshire in the UK, Schleswig-Holstein, Bavaria in Germany; Wire-based technologies applied to this area are mainly steered by Cataluña and Bedfordshire.
152 See http://www.gkn.com/hoeganaes/products/Pages/Additive-Manufacturing.aspx
153 See http://www.technology-licensing.com/etl/int/en/What-we-offer/Technologies-for-licensing/Metallics-and-related-manufacturing-technologies/Scalmalloy.html
154 Source: Coykendall et Al., 2014
155 For example companies such as Eurasteel EU or Metallo-Chimique N.V. (BE), TLS (DE), LPW (UK), Constellium (NL), Google (US), ATI (US), AMPS (Australia), Sandvik (SE), H.C. Starck (DE), or Carpenter (US).
156 Aubert et Duval (FR), Valimet (US), TLS (DE), NMD (DE), and ECKA Granuls (DE) were identified by the interviewees.

OEMs such as GKN (UK) are however developing in-house capabilities in that respect[157,158]. Powders are however not the only form of raw material as also arc wire systems are being developed in Spain and the UK and now going through demonstration. Companies also propose Electron Beam Melting as an alternative to the Selective Laser Melting or Sintering options. As a result, German players such as EOS, SLM Solutions and ConceptLaser and their European counterparts Renishaw[159](UK) and Arcam AB (SE) are competing with different arguments. The systems developed call upon operating software which are sold by a few companies such as Materialise (BE), Stratasys (US) and NetFabb (DE) dominate the market while the CAD market is more open to international competitors including Dassault (FR). Tiers 1 and 2 in this value chain are large multinational companies making large investments in AM (GE for instance invested over $1B in R&D[160] to develop, produce and distribute AM fuel nozzles). They collaborate with printer manufacturers but also AM service providers. This leads the value chain towards more decentralization. French service providers (Airpro, Polyshape, 3A, FUSIA, Spartacus 3D, Sokaris, PRISMAD, Polyshape, and Mecachrome) are particularly active in the field. These providers also collaborate with integrators (Airbus, Boeing, Bombardier[161], Dassault are the usual suspects)[162]. Airbus remains a central player in Europe as it developed bionic titanium brackets[163] for the A350 XWB[164]. Also RTOs are closely collaborating with the aeronautic industry (in Western European Regions mainly)[165]. Collaborations are also existing across value chains are the same companies active in the aeronautic field have links with both defense and space sectors. Also collaborations between aeronautic and automotive industries were referred to. Development areas include monitoring, control, large and complex parts integration.

BARRIERS AND POLICY IMPLICATIONS. Tooling, life-cycle management, and in particular prototyping and mainstream production are seen as the upcoming fields of use of AM in A&D (Defense IQ, 2016) for a faster production of larger parts, multi-material printing and printing of embedded parts (Automotive IQ, 2015). Some interviewees see AM of mechanically loaded parts as a first step. Material-related evolutions towards an increasing use of composite materials in structural parts in airplanes (as supported by Canaday, 2015) might also be foreseen; but these developments, should they effectively take place, might take decades. As competition is rising from China[166] but also from the US regarding the increasing use of polymers and composites (including ceramic-based) in AM, metals therefore remain the most appropriate type of material for structural parts. Metal AM for structural aircraft components is however hampered by several factors: the sector is heavily regulated and concerned with lengthy development plans that might not have foreseen the rise of AM. In addition, knowledge and skills are still to be improved. As highlighted by interviewees, the need for common standards and further characterization of the materials and processes should come with better knowledge about the health and security implications of using AM for production. In addition, AM faces scalability issues which makes the printing of large sizes difficult[167]. In general, quality and surface finishing are not optimal. Detection, monitoring and control of surfaces are to be developed further to contribute to reach quality expectations. Moreover, quite critical is the lack of transformation capabilities in Europe and the availability of high-class, passivated clean powders, including **aluminum, magnesium and titanium**[168] which require high levels of investment. Finally, the lack of streamlined information and insufficient awareness are critical to help overcome the 3D-printing hype but also to promote the use of AM for where it adds value. Policy implications were derived from these conclusions and it is possible to point at the need to:

1. Facilitate the access to critical materials (titanium, aluminum, magnesium, etc.) by developing transformative capabilities. Initiatives at all government levels could be undertaken to support R&D in the field but also to set up relevant networked infrastructures (pilot production, demonstration, etc.).
2. Support R&D by co-investing in key development areas (material feedstock, quality control, toxicity of the materials, multi-material printing, hybrid manufacturing, etc.) through cross-regional R&D projects and networks but also tax incentives (R&D tax credits, etc.).
3. Develop capabilities in testing, finishing, post-treatment, and demonstration. Direct support could be brought by all levels of government in that regard.

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157 Source: http://3dprint.com/59084/tipow-research-collaboration/

158 Source: http://www.gkn.com/media/News/Pages/GKN-Aerospace-commences-collaborative-research-to-create-additive-material-for-aerospace.aspx

159 See http://www.renishaw.com/en/renishaw-supports-uk-government-funded-additive-manufacturing-aerospace-initiative--27335

160 See http://3dprintingindustry.com/2014/08/11/3d-printing-ge-jet-engine/

161 Airbus and Bombardier are mainly working on the AM of primary structure applications, driven by titanium components used to join components (of less than 3m) of the structure together (for instance with direct deposition techniques) and the growing use of composite materials.

162 Besides the usual suspects, Lockheed Martin also acquired Sikorsky in Poland.

163 See http://www.a350xwb.com/photo-gallery/ and http://www.airbus.com/presscentre/pressreleases/press-release-detail/detail/printing-the-future-airbus-expands-its-applications-of-the-revolutionary-additive-layer-manufacturi/

164 The firm also plans to "3D-print around 30 tons of parts monthly by 2018" and involved around 60 employees in about 120 AM projects in Germany (source: Wohlers, 2015).

165 Sør-Trøndelag, North Rhine-Westphalia, Hamburg - Low Saxony, Bavaria, Hesse, Rhône-Alpes, South Holland, Ile-de-France, Veneto, Emilia-Romagna, Bedfordshire and Lancashire.

166 See http://3dprint.com/82169/3d-printed-aircraft-parts/

167 Except for wire-based technologies, AM is only concerned with parts of limited sizes.

168 Titanium 6.4 or titanium aluminide for instance.

4. Develop new curricula and develop appropriate skills at the level of the European workforce and under the coordination of the European Union.
5. Streamline standardization efforts at the European level by centralizing most of the on-going processes to the extent possible.
6. Streamline information in order to develop a repository common to all players of the innovation system (this could for instance take the form of a permanent and up-to-date website dedicated to AM information relevant to industry and labelled by the EC services or externalized to a dedicated one-stop-shop).
7. Foster collaborations along and across value chains (for instance linking defense, automotive, space, aeronautics, transports) on common AM issues. Collaborations could concretize through shared platforms, networks or collaborative projects on specific applications (structural titanium-based components for instance) or on specific processes (wire-based AM systems to produce vehicles' structural parts).
8. Rise awareness across the user community to manage the transition towards AM-inclusive manufacturing[169]. Appropriate events with an EU label could be a reliable option in that respect.
9. Stimulate the development of wire-based technologies by taking advantage of the current demonstration projects. Support to cross-regional pilot production and demonstration projects and facilities would therefore be welcome in that respect.
10. Stimulate demand for AM in the sector, for instance through policy tools and instruments such as regulation.

4.2.4 Inert and hard implants

CONTEXT. AM is known in the field of healthcare for its customization and optimization potential (Ventole, 2014). The top three of the most promising markets for additive manufacturing identified in healthcare are Additive Manufactured organs (estimation of 3 billion dollar market in 2025), personalized implants (estimation of 30 billion dollar market in 2025) and printed medicines[170]. Wohlers (2015) estimates that the Food and Drug Administration (FDA) has already provided clearance for more than 20 different additive manufacturing medical implants. It concerns, among others, cranial implants, hip, knee and spinal implants. Of the acetabular (hip cup) implants, already 100,000 units have been produced, of which about 50,000 have been implanted into patients (Wohlers, 2015).

SCOPE. Inert and hart implants are divided into three main categories: Orthopedic, cranio-maxillofacial and dental implants. As dental implants are considered to be a mature market[171], the first two sub-areas were retained for this case study. The case therefore encompasses the following two types of applications (see also Figure 13):

- An orthopedic implant is a device surgically placed into the body designed to restore function by replacing or reinforcing a damaged structure. There are different types of orthopedic implants: Hip, should and knee. A hip implant consists of the following three parts: the acetabular cup, the femoral component, and the articular interface. Acetabular cups are very often printed and placed in the hip socket (acetabulum). The lattice structure improves osseointegration172.
- Cranio-maxillofacial implants are used during cranio-maxillofacial surgery which refers to a procedure used for the treatment of severely injured cranial or facial bones173. Cranio-maxillofacial implants are thus used for facial and skull reconstructions.

Figure 13: From left to right, a) a custom cranio-Maxillofacial implant and b) an acetabular cup with lattice structure

Source: Arcam[174]

[169] It has been acknowledged by the interviewees that the use of AM was not optimal and that particular corporate levels in large user organisations are subject to organisational conservatism – slowing down the speed of diffusion of AM.

[170] http://www.fabulous.com.co/blog/2015/11/impression-3d-medecine-medical-sante-quel-marche/

[171] EOS indicates that their additive manufacturing equipment already produces more than 5 million metal copings, which are used to produce crowns and bridges, every year (Wohlers, 2015).

[172] https://scrivito-public-cdn.s3-eu-west-1.amazonaws.com/eos/public/b674141e654eb94c/c5240ec3f487106801eb6963b578f75e/medicalbrochure.pdf

[173] Transparancy market Research: Press Releases http://www.transparencymarketresearch.com/pressrelease/craniomaxillofacial-implants-market.htm

[174] http://www.arcam.com/solutions/orthopedic-implants/

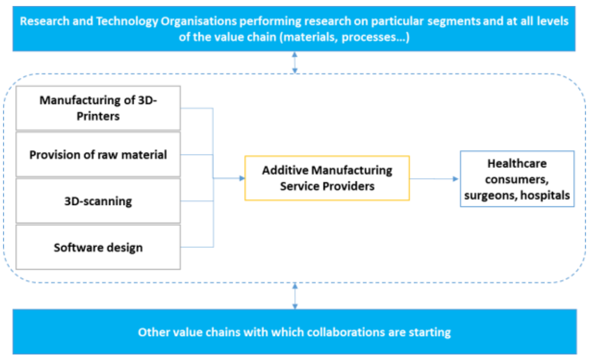
There are different categories of additive materials: polymers, metals, ceramics and biological cells. Overall, the two major categories of additive materials are polymers (incl. polyetheretherketone or PEEK, a material resistant to simulated in vivo degradation, including damage caused by liquid exposure[175]) and metals such as titanium or cobalt-chrome alloys (Wohlers, 2015). AM usually allows for complex and customized implants. With some materials the porous nature of the additive manufactured implant also allows the bone to grow into the implant which creates a natural bond with the body[176].

VALUE CHAIN. The application area therefore focuses on orthopaedic and cranio-maxillofacial implants and underlying segments of the inert and hard implants value chain. In Europe, the important actors involved in the 3D-printing of such applications are mainly located in EU15. Eastern European actors are often involved in only one segment of the value chain whereas several companies in EU15 are involved in multiple segments among which 3D- scanning (which is not a segment found in all value chains but is of main importance for this set of applications). From the side of scanning CT (computed tomography) scan is used most frequently. For soft tissue structures and cartilage, magnetic resonance imaging (MRI) is often applied. A broad range of EU incumbents can be found on this segment. The software segment is however dominated by Materialise (BE) and 3D-Systems (US) who develop both interface and CAD capabilities. Companies such as ARCAM (SE), EOS (DE) and Optemec (US) usually provide metal powders while Oxford Performance Materials (UK), EOS (DE) and Stratasys (IL) provide polymers (incl. PEEK).

3D-printers from companies such as 3Dsystems (US) via its Layerwise branch in Belgium, Stratasys (IL), EnvisionTEC (DE), Renishaw (UK) and Arcam (SE) are used to manufacture such implants in Europe. They also act like service providers and compete with companies such as Materialise (BE)[177] active in the area via Mobelife[178]. Some smaller companies focus on the customized implant market (e.g Xilloc, NL) and provide hospitals and AM service providers with services. Large orthopedic companies are technology followers and combine traditional and additive forms of manufacturing for large-scale production. These are Johnson and Johnson (US), Stryker (US) and Zimmer Biomed (CH), Oxford Performance Materials (US), Smith and Nephews (US)[179] and Medacta (CH).

At the very end of the chain, implants are provided to the hospitals where the surgeons implant them in a patient and who decides whether to go or not for a 3D-printed implant. Hospitals are also collaborating with RTOs[180], themselves collaborating with industry on material, medical imaging as well as AM systems.

Figure 14: Main segments of the hard and inert implant additive manufacturing value chain



When considering other value chains, connections are mainly found at the level of AM service and printer suppliers who are also active in areas such as aerospace, healthcare, automotive and where similar materials (PEEK for instance) are being researched. In the near future (5 years), it is expected that the use of biodegradable material will overcome the testing phase. The printing of biological cells or Bioprinting is expected to develop until (within 20+ years) organs can be printed. A more speculative expectation is that implants or organs will in the future be printed in the human body during surgery (i.e. in situ printing). The in situ bioprinting for the reparation of external organs such as skin, has already occurred[181]. Import for the evolution in in situ bioprinting might be the advancements in robotic bioprinters and robot-assisted surgery. The key markets in global 3D-printing in medical applications are Europe, North America and Asia Pacific. North America was the dominant market in 2012 but economic conditions in Europe are more conductive, stimulating market growth, and possibly allowing Europe to surpass North America by 2019[182] (Transparence Market Research, 2015).

175 Kurtz, S.M. and J.N. Devine (2007) PEEK materials in Trauma, Orthopedic and spinal implants. Biomaterials; 28(32): 4845-4869.
176 http://3dprint.com/12253/3d-printed-vertebra/
177 3D-printing in medical applications market (medical implants, surgical guides, surgical instruments, bio-engineered products) – global industry analysis, size, share, growth, trends and forecast. Transparency Market Research. September 15th, 2015.
178 http://biomedical.materialise.com/cases/3d-printed-hip-puts-teenager-back-her-feet
179 http://www.smith-nephew.com/about-us/what-we-do/orthopaedic-reconstruction/
180 NewCastle University, Warwick University, Loughborough university, Nottingham University (UK), KU Leuven (BE) as well as in Germany, Italy, Spain, France.
181 Ozbolat IT, Yu Y. Bioprinting towards organ fabriation: challenges and future trends. IEEE Trans Biomed Eng, 2013;60(3): 691-699.
182 http://www.medgadget.com/2015/09/3d-printing-in-medical-applications-market-future-trends-and-forecast.html

Current capabilities for the present application area are concentrated in Western European regions where players such as Materialise (Flanders), SIRRIS (Wallonia), Layerwise (3DS branch in Flanders) collaborate with more classical incumbents like Medicrea[183] (Rhône-Alpes) or large healthcare players such as the ones listed in the above sub-section. Denmark, France, Italy, Spain, the Netherlands and the United Kingdom are the main countries where capabilities were found. While system manufacturing capabilities are found in Sweden[184] or Germany (Bavaria for instance[185]), service providers and RTOs are also found in Asturias, Emilia Romagna, Flanders and Wallonia. Also American players are involved (such as Shapeways, founded in the Netherlands and with offices in Eindhoven but headquarted in New York).

BARRIERS AND POLICY IMPLICATIONS. Users are quite important for this value chain as they remain a bottleneck to the adoption of AM. The ability to produce customized implants is important in orthopedics as surgeons do not need to perform bone graft surgeries or use scalpels and drills to make the implant fit. Customized implants allow for less adjustments of the implant during surgery, shorter surgery times and less follow-up surgeries. Barriers to the further uptake and deployment of AM remain however. The regulatory framework together with uncertainties regarding the certification of (customized) implants hamper the deployment of AM whether the implant is standard or customized (and therefore subject to different procedures). A first step in the improvement of the regulatory framework is information flow. There is overall still a lot of uncertainty with respect to the steps to certification in Europe. In the US, the FDA is in charge of approval of medical devices and it seems to be clear which steps companies have to take in order to get an FDA's 510(k) approval. Not all companies in Europe are well informed about the certification conditions/requirements.

Box 15: Missing and/or under-developed capabilities in this value chain include...

- Capabilities are mainly concentrated in Western European regions;
- Software (incl. simulation/modeling) capabilities should be further strengthened in the sense of customisation.

Also IPR and more specifically the "ownership" of a design is seen as a possible challenge for the future. But technical isssues remain in the first place: e.g. the quality of relevant materials, the userfriendliness of the 3D-printers, the complex design phase etc.. The knowledge on the (quality of) materials in particular are perceived as a missing capability Europe (see Box 25). Research with respect to the porosity and strength of the material needs to be stimulated. Such development goes hand in hand with the right (multidisciplinary) skills and technology development (including R&D/characterisation and standards) to improve the strength and size of the products under the scope and shorten the digital design phase. Finally, surgeons and hospital managers are not enough aware of the benefits of AM. These barriers lead to several policy implications, which are the following:

1. Certification processes with respect to the production and use of inert and hard implants should be streamlined at both national and European levels.
2. IPR enforcement (for e.g. design) is necessary to reduce the risk-avoiding behaviour of most companies from the traditional implant market. Harmonisation at the national and European level is necessary
3. (multidisciplinary) Skills and appropriate training/education should be developed (at national level, with EU coordination to obtain a level of harmony and diversity between Member States)
4. (multidisciplinary) collaborative R&D support is required to foster the development of areas where there are still some missing capabilities and/or future/emerging areas such as biodegradable materials, material properties, diagnostics and sensoring, etc., this at all government levels.
5. Awareness should be raised and information streamlined and diffused to surgeons and hospital managers at the EU level. Relevant target groups are doctors, patients, healthinsurance (with respect to reimbursement) and government institutions (institutes for healthinsurance).

183 Medicrea is a French company that specializes in the design, development, manufacturing and distribution of orthopedic implants dedicated to spinal surgery. See http://3dprint.com/8821/3d-print-spinal-cage/ .

184 See http://www.arcam.com/solutions/orthopedic-implants/

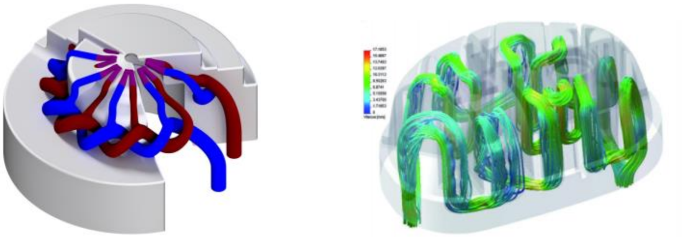
185 See for instance http://www.eos.info/industries_markets/medical/orthopaedic_technology

4.2.5 Metal AM for injection Molding

CONTEXT. The machinery and tooling sector was particularly hit by the 2008 financial crisis and currentl suffers from a weak internal consumption in Europe and a declining position world-wide, while Asia –and China in particular– is on the rise (Geerts, 2013). According to CECIMO[186], in 2014 the European machine tool production recorded growth and reached to 23.1 billion euros[187]. The volatility in the industry is due to its position on different value chains. Major countries for the machinery and tooling industry are Germany, Italy and Switzerland. Europe occupies an important position in the sector, although China and Japan also occupy a dominant position (with respectively 22% and 19% of the global machine tools production share in 2014). 80% of CECIMO's production is exported with 46% of exports outside Europe[188].

SCOPE. The sector also covers AM and counts with companies involved in both AM and the production of other industrial machines. This case is however focused on on the tools used in the manufacturing process and not on machines. The additive manufacturing of tools correspond to "*secondary services*"[189] and cover "*tooling produced from AM patterns, tooling components produced directly using AM, and molded parts and castings produced from this tooling*" (Wohlers, 2015). Tools such as molds, casts and dies can be defined by their use (while tools are used to cut and form materials for instance, dies are used in forging as to shape metal. Although CNC remains more cost-effective, AM is being increasingly used for tooling, including when coming to print molds, castings and patterns. AM was however mainly developed for molds. Only few cases of cores and patterns could be identified[190]. AM is used where it adds most value e.g. where small (or even unitary) series are to be produced, and where technical challenges require the use of a non-traditional technology. It is therefore of particular interest for the molding industry where inserts are printed with AM and then added on the molds. One of the main advantages of AM in the field of molding is related to conformal cooling[191] (see Figure 15) to improve technical characteristics and reduce cycle times: with AM, there is no need to dig straight holes in steel molds as it is now possible to optimized cooling channels in molds that are printed with Maraging steel[192] or other metals for instance.

Figure 15: Conformal cooling channels



Source form left to right: Melotte[193] and Pôle Européen Plasturgie[194]

The focus was placed on metal AM for injection molding, as it is a mature area where AM is not fully deployed yet but is seen as a great deal of promises[195]. AM molds are more expensive to make, but these molds are far more efficient and therefore lead to savings. They are usually made of metal (aluminum, etc.). Other areas (die casting, sand casting, blow molding, compression molding) under the scope are either concerned with a too early development stage of AM or/and less leverage potential. Injection molding is an area where AM can have a disruptive potential, also with regard to other molding segments which are shrinking as companies turn to injection molding. It is a fast-growing area where AM shows an intermediary level of penetration.

[186] CECIMO represents 15 national associations of machine tool builders, "o*ver 1400 industrial enterprises(...)approximately 80% of which are SMEs. CECIMO covers more than 98% of total machine tool production in Europe and about 39% worldwide. It accounts for over 150,000 employees globally.*" (Source: http://www.cecimo.eu/site/the-industry/data-statistics/latest-trends/)

[187] Source : http://www.cecimo.eu/site/the-industry/data-statistics/latest-trends/

[188] Geerts, 2013; and CECIMO, http://www.cecimo.eu/site/the-industry/data-statistics/latest-trends/

[189] Secondary market includes additive manufactured tools and related products produced with these tools.

[190] See the soluble cores proposed by Stratasys (http://www.stratasys.com/solutions/additive-manufacturing/tooling/soluble-cores) and the offer from the Richland Center Foundry (http://www.rcfoundry.com/iron-casting-expertise/industrial-additive-manufacturing) for instance;

[191] It allows to make molds more efficient thanks to conformal cooling and the diminution of cycle times (by 50% in some cases). See http://www.melotte.be/en/3d-metal-printing/reference/conformal-cooling

[192] Iron alloy with superior strength – see for instance http://www.imoa.info/molybdenum-uses/molybdenum-grade-alloy-steels-irons/maraging-steels.php

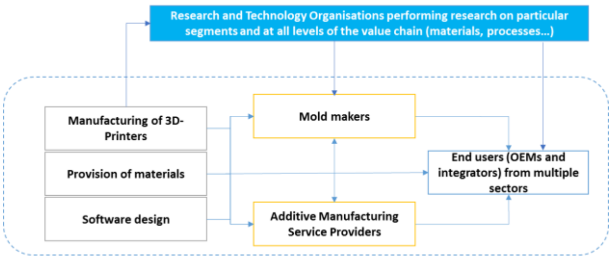
[193] See http://www.melotte.be/en/3d-metal-printing/reference/conformal-cooling

[194] http://www.poleplasturgie.net/presentation-du-pep.html?file=pep/documents/plaquettes/Procedes%20et%20Outillages%20-%20Conformal%20Cooling.pdf

[195] Although the aforementioned casting techniques are concerned with limited series, molding techniques can have a leverage effect in large production series. Injection molding in particular is indeed used for large-scale production.

Metal-based AM technologies such as fused metal deposition (FDM[196]) or Selective Laser Melting (SLM) of inox or Maraging but also Selective Laser Sintering[197] are the main technologies used in this value chain as they are the only ones providing a good enough level of granularity.

Figure 16: Main segments of the injection molds additive manufacturing value chain



VALUE CHAIN. Many companies are active in this area. They very often combine AM with more traditional manufacturing methods (CNC, etc.). In Europe AM is particularly used by companies active in Western European regions, most likely because relevant AM capabilities are mainly concentrated in these countries[198]. The value chain is heterogenous and subject to a very high level of fragmentation as most companies are small (and even micro-)companies. These companies are active across a broad range of value chains and sectors, from car manufacturing to the quality control of agro-food products. Printer manufacturers (EOS, Trumpf, Concept Laser, etc.)[199] supply both mold making and end-user industries. The same goes for service providers like Melotte and Materialise (Flanders). All face competition from US-based and Japanese providers (3DS[200], Stratasys and ExOne from the US; and DMG MORI as well as KEYEMCE from Japan) who offer hybrid systems. They play a facilitating role in the process of adoption of AM in these two segments of the value chain, similar to the one plaid by service providers[201].

RTOs and in particular technical centers[202] are also key enablers in that regard: they provide SMEs with relevant support to demonstrate the value of AM and foster its discovery but also the development of capabilities in companies when relevant. They are of main importance to SMEs who do not have the skills and financial capabilities to acquire and run 3D-printers, but are also perceived as competitors as they collaborate with larger OEMs and integrators who are the historical clients of mold-makers. In general, mold-making companies are at an early stage of adoption, and only lead users manage to test and acquire AM. However, large end-users such as EOMs or integrators (car manufacturers, main airplane manufacturers, etc.) are also using AM and are currently integrating the complete process in-house. Pentagon Plastics in the UK[203] or Schneider International[204] are examples of companies who developed AM capabilities. Pre-series for large scale productions is the subject of many requests received by service providers[205]. The pre-series production is an important business area for the service providers producing between 10 000 and 20 000 parts. Other companies such as Lego (DK), Unilever (UK, IT), Rowenta (DE), IKEA (NL), Berker (DE), L'Oréal and nestlé (FR) make use of metal molds. Raw materials to print the mold inserts are provided by a large panel of providers as different kinds of metals can be used (from maraging to aluminum) by global players such as Erasteel and GKN (North Rhine-Westphalia), Sandvik (Flanders), Höganäs (Skåne), and LPW (Cheshire); or North America[206]. When paying attention to the software segment, one can notice that European players such as Dassault (FR) or Altair (DE), Netfabb (DE), and Materialise (BE) hold a central position but still face competition from US-based firms (Moldex3D, Stratasys, etc.). The value chain is now subject to potential major changes: with AM, OEMs and integrators can print their own molds; they can also develop in-house AM capabilities. A complete substitution of AM to traditional mold-making techniques could be possible when traditional techniques are not cost-efficient anymore compared to what AM can offer. A clear concentration is however formed in the

196 Which stands for Fused Deposition Modelling

197 Other techniques can be mobilised to fabricate plastic-based molds in specific cases such as what Stratasys (US) or OMEGA Plastics (UK) do (see http://www.omegaplastics.com/our-technology/); they however represent a much narrower part of the industry under the scope in Europe.

198 Besides well-known providers such as 3DS (US), Stratasys (IL), EOS (DE), Renishaw (UK), or VoxelJet (DE), Schneider Prototyping and MK Technology GmbH (DE), Pentagon Plastics and Omega Plastics (UK), CA Models (Scotland) and Laser Prototypes Europe (Northern Ireland) are examples that can be found on http://wohlersassociates.com/index.html

199 HK 3D (3DS, Warwickshire), Renishaw (Staffordshire), SLM-Solutions (Schleswig-Holstein), EOS (Bavaria), Voxeljet (Bavaria), ExOne (Bavaria), ConceptLaser (Bavaria), Protolabs (Baden-Württemberg), 3DS through Phenix Systems (Auvergne) and its UK-based HK 3D branch

200 Through its Phenix Systems branch in Auvergne (FR) and its partnership with HK 3D in Warwickshire (UK)

201 Protolabs (present in several EU countries) has for instance its EU headquarters in Mosbach (DE). Other companies like Melotte (BE), Brugges Raytech (BE), Layerwise (BE, now 3DS), CA Models SL (Scotland), MK Technology GmbH (DE), and Laser Prototypes Europe SL (Ireland), FIT (Bavaria),Initial and Shapeways (both Gorgé, Rhône Alpes and Ile-de-France).

202 Sintef (NO), Fraunhofer (DE), TNO (NL), Ecole des Mines (FR), the Universities of Munich, Dusseldorf, and Freiburg (DE), the University of Zurich (CH), The von Karman Institute for Fluid Dynamics (BE), the Laboratoire IRTES LERMPS (FR), CETIM (FR), PEP (European Pole of Plasturgy, FR), the Technological Centre for Mouldmaking, Special Tooling and Plastic Industries (CENTIMFE, PT), VTT Technical Centre of Finland (FI) as well as the Brno University.

203 See http://www.pentagonplastics.co.uk/uk-mould-tools/

204 See http://www.schneider-prototyping.co.uk/company.html

205 FIT in Nuremberg for example, is mainly active in producing molds and pre-series' parts for the automotive industry. Also Polyshape (now Gorgé, FR) produces pre-series of plastic clips via AM-built molds.

206 A longer list could include Eurotungstene (FR), Erasteel (DE), LSN Diffusion (UK), ATI – Specialty Metal Supplier (US), Sandvik (SE), LPW (UK), Metalysis (UK), Advanced Powders & Coatings (AP&C) (CA), TLS Technik (DE), Nanosteel (US), Carpenter (US), CVMR Corporation (US), Plansee (AU) and GKN (UK)

value chain at the level of 3D-printer manufacturers. These manufacturers are currently disrupting the value chain for instance by providing companies with printers that allow for conformal cooling.

BARRIERS AND POLICY IMPLICATIONS. When considering current and emerging trends, several developments can be mentioned. Particular applications are visible in the automotive sector where thermal exchangers, light components, and new solutions for gearbox are among the molded components where AM could add value in the coming 5 years. Also the packaging sector is concerned with very large series. AM-enabled molds might therefore have a significant leverage effect on this sector. This sectorial dimension is important as the bargaining power is concentrated in segments down the value chain: users (and not suppliers) are usually steering innovation through their demand and product specifications. From a technical viewpoint the development of hybrid systems but also new materials are key: thermo-plastics injection molding is in that respect the main sub-sector able to innovate and steer change in the industry. It is also where AM is most developed for injection molding. Pre-series production and prototype molds but also the development of fully digital solutions are emerging areas to become key in the near future.

Box 16: Missing and/or under-developed capabilities in this value chain include...

- Transformative capabilities in high-end powders;
- AM Supply capabilities are mainly concentrated in Western European regions and the users are part of a scattered landscape;
- Software capabilities could be further strengthened to face international competition.

Still barriers face the deployment of AM along this value chain. Printers and related powders remain expensive and SMEs have no or little (financial/HR) capacity to buy and use AM. Their access to AM is therefore insufficient. This situation is not eased by AM system manufacturers who struggle to meet the growing demand for printers and are not yet fully competing on prices. In addition the mold-making industry is rather culturally conservative and lacks of AM awareness. Demonstration activities were particularly pointed as a weak point of Europe to convince companies that AM brings value to mold inserts. This also goes through a skilled workforce: multi-disciplinary curricula are still to be developed in that regard. Knowledge can also be seen at the level of the technology: AM is subject to technical limitations (cleaning of cooling channels, printing of large molds, precision and surface finishing, etc.). This calls for further qualification but also further certification of AM processes and materials as well as further research. Regarding materials, the transformative capabilities (players able to turn certain metals into powders) are said to be under-developped in Europe (see Box 16). Moreover, a few players are standing as bottlenecks in the field of metal powders[207]. Also competition issues were spotted: mold-makers are afraid that software and service providers but also OEMs and RTOs steal their designs or replace them on their segment of activity. As client companies (OEMs and integrators) also develop internal AM capabilities and SMEs have little bargaining power, the latter bear the cost of AM. Threats also arise from foreign economies and the field of plastics and composite materials. Policy implications to be addressed by public authorities are therefore as follows:

1. Co-investment in AM is required to compensate for the high costs of AM. Schemes to foster the access of SMEs to relevant AM capabilities (through innovation vouchers for instance) are deemed relevant in that respect.
2. Information diffusion and awareness raising activities should be implemented to support the adoption of AM in the sector and in order to foster the success of demonstration support needed to facilitate the adoption of AM (especially by SMEs).
3. Support should be brought the development of transformative capabilities in key powder fields such as titanium and aluminum. This implies to facilitate the access to market intelligence and business development conditions, co-invest in relevant activities (transformative technologies for instance), accelerate the qualification and standardisation of powders and other forms of AM materials, but also develop collaborative approaches to qualification and explore new perspectives such as urban mining.
4. Cross-regional demonstration activities should be supported as well as joint actions and collaborations among exising actors, whether on a case-by-case basis or through (a) one-stop-shop(s). This would allow a better connection between supply and demand as well as to flow knowledge and network towards Eastern European regions.
5. In addition, support is to be brought to emerging areas (multi-material printing, digital design – and in particular numerical simulation, hybrid manufacturing, etc.) for which R&D support is missing and which could take the form of cross-regional collaborative R&D projects and networks.
6. Skills and curricula should be developed in a multi-disciplinary fashion under the supervision of the European Commission.
7. IPR are not a barrier as such, but could support the deployment of AM along this value chain. IPR regimes should be enforced in view of possible growing infrangements and in the first place ensure that SMEs are confident to use AM, with particular attention to be paid to design patents and copyrights linked to original molds and parts that could be reproduced.
8. Awareness should be raised across mold-makers but also users (OEMs and integrators) and depending on the value chain consumers who constitute the demand side of the value chain. Web-based channels and dedicated events could be a viable option in that regard.

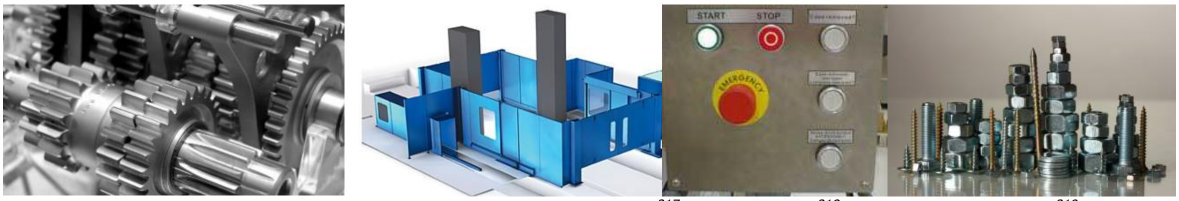
207 e.g a printer manufacturer conditioning the use of its printers to the use of its powders.

4.2.6 Spare parts for machines

CONTEXT. The machinery industry is historically connected to a broad range of sectors[208]. Despite of the competition rising from Asia[209] CECIMO's countries[210] reached a €23.1 billion production output in 2014, with Germany, Italy and Switzerland in leading positions[211]. AM is a growing[212] sub-sector[213] of the machinery and tooling sector. It has therefore particular ties with the broader machinery area. According to Wohlers (2015), 17.5% of AM systems is sold to players involved in the sector of industrial and business machines. Although it remains a small industry compared to the overall €60B machine tool market, it is expected that the AM market grows exponentially in the coming ten years[214]. AM is in general expected to make existing supply chains more efficient by reducing inventories and spare parts, allowing for localized and on-demand production (GAO, 2015) which also applies to the machinery sector. Industrial machines can indeed be expensive and crucial to production processes.

SCOPE. The AM of spare parts is a topic that was researched in a number of areas such as Aerospace, Automotive and Military[215], in some cases with substantial support from FP funding[216]. However, in most cases the focus was on the production of parts for end products and not spare parts for machines. Also companies like Siemens (DE) and GE (US) mobilise AM for the production of spare parts of domestic appliances or gas turbines (De Wever, 2015) in collaboration with printer manufacturers such as EOS (DE). In addition to spare parts for other end products, AM of spare parts for machines is also promising. In the US for example, inventories are currently estimated to stand at $1.7 trillion or 10% of the American GDP (Source: Graham Tromans in CECIMO, 2015). The area selected during the first phase of this project is entitled "*Spare parts for machines (e.g. gears, housings, buttons, and fasteners)"* (see Figure 17) and has a strong potential for cross-value chain impacts.

Figure 17: Machine gears, housings, buttons and fasteners



Source (from left to right): Industrial Gears Manufacturer[217], KabelSchlepp[218], Machinery Safety 101[219] and Melfast[220]

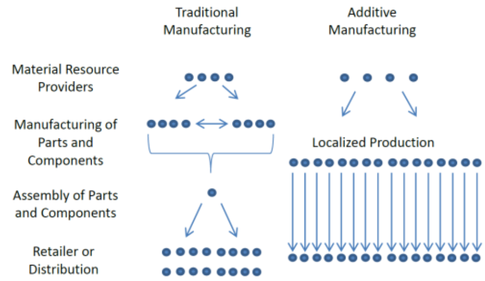
It has however not been possible to narrow down the scope of the area due to a lack of information concerning applications that have really be tested in practice. No case of AM of the elements under the scope of this case could be found by the team that showed a level of satisfactory level of maturation. The area was therefore broadened again to spare parts for machines. This encompassed a broad range of possible parts. From the literature review and interviews, only a few experiences could however be reported that are mainly to be associated with a stage of experimentation, rather than effective use aiming to turn the current supply chain(s) into more efficient chains. There is no main reference framework dedicated to the categorization of spare parts for machines. Machines however encompass a number of components (most of them recurrent) for which spares can be needed[221]. A broad range of parts could therefore virtually fall under the scope of this case study, whether plastic or metallic parts, or whether mechanical elements[222], structural elements[223] or elements used to control the machine process[224]. Among these elements, both "*repairables*" (repairable parts, usually modular) and "*consumables*" (parts that do not last) could benefit from AM as AM could be mobilized either to replace failing parts or produce replenishment spares. AM could also lead to distributed manufacturing (Figure 18) of spares. Although the specific elements under the

208 Source : Vieweg et Al., 2012
209 Main Asian competitors include China (with 22% of production share) and Japan (19%) followed by South Korea (7%) and Taiwan (6%). United States and Canada only share a small share of the world-wide production (respectively 6% and 1%).
210 CECIMO represents national federations from 15 EU countries, covers more than 99% of the total machine tool production in Europe and 30% worldwide and accounts for about 1500 companies among which more than 80% are SMEs fir almst 150 000 employees (See http://www.cecimo.eu/site/about-us/).
211 See http://www.cecimo.eu/site/the-industry/data-statistics/latest-trends/
212 AM grew by 20% between 2004 and 2014 and grew by 30% between 2010 and 2014 (Roland Berger, 2015).
213 About 30% of the AM market covers machines (including system upgrades and aftermarket services), while about 50% concerns services and about 20% materials. See Roland Berger, 2015
214 Source: Roland Berger, 2015
215 A lot of research is being conducted in the United States on the on-site use of AM to produce spares directed to military or space uses – see for instance Khajavi et Al. (2014) and NASA (2015).
216 See http://www.materialise.com/cases/bringing-back-the-spirit-of-a-classic-sports-car and www.direct-spare.eu
217 See http://www.industrialgears.in/blog/applications-of-different-industrial-gears/
218 See http://kabelschlepp.de/en/products/machine-housings/index.html
219 See http://machinerysafety101.com/2009/03/06/emergency-stop-whats-so-confusing-about-that/
220 See http://www.melfast.com/blog/2014/11/how-to-determine-what-fastener-types-to-use-for-industrial-machine-construction/
221 Pinions and gears, pipes, helical shafts, sprockets, but also clutches, drag brakes, slip couplings, electric motors and controls, machine frames, welded joints, fasteners, etc.
222 Without which the machine cannot function – such as gear trains or clutches.
223 Axles and fasteners for instance.
224 Buttons, sensors, etc.

scope (gears, housings, buttons, and fasteners) were not subject to AM, other machine parts were tested by different organisations as to prove the potential of AM. These cases however remain at a low maturity level as they mainly consist in researching and testing.

VALUE CHAIN. The value chain under the scope does not exist yet and is slowly emerging. Only key platforms seem Only isolated cases could be identified, mainly steered under the seal of secrecy in large multinational firms. AM is seen as a differentiating technology and most companies do not disclose any information about their use of AM for machines. It was however possible to identify the Baden-Württemberg, Dutch North Brabant and Flanders as key regions for this value chain though they are at an exploration phase. All industries oriented toward mass production and making use of heavy machinery are however potential beneficiaries of AM. Expensive machines[225] (such as to press metal sheets) are indeed expected to function for decades, making the access to spares potentially difficult as the provider might stop its product line or get bankrupt. AtlasCopCo (NL) made public its investigation about AM applications[226] and related savings while using a VIL[227] methodology (see Corne, 2015). The simulation shows in some cases cost reductions of about 35% but a limited potential for metal AM which is perceived as too expensive. A case opportunity cost was however identified regarding the AM of brass couplings for which suppliers have stopped production and for which replacement imply the replacement of the pipes on the related compressor (and therefore a high service cost). In some cases, the use of AM for spare parts would lead to a maintenance time reduction of 90%: this is the case of Siemens' burner tips for use as replacement parts in gas turbines that are being manufactured by AM. Other components under scope, such as "*sparovation parts*" (Huber, 2015) are part of the services provided by Siemens[228] as an AM spare part provision service.

Figure 18: Turning to efficient and distributed manufacturing



Source: Douglas and Gilbert, 2014

In the field of **machining solutions**, ASML claims to have 30 parts in AM production and demonstrated a 90% reduction of disturbances in PEEK and titanium components thanks to AM, with and thermal control improvements on conditioning rings by 6 times together with better dynamics improved by 15% (Loncke, 2015). In the **packaging** industry, IMA.it collaborates with BC and came to the conclusion that the focus should be put on non-precision constrained machine parts. This investigation also demonstrated the potential of delocalized production of spares to reduce the costs associated to logistics. Despite of the secrecy and early development stage of this area, companies[229] were however identified by the interviewees as companies researching or presenting an interest for AM. These companies are most likely to collaborate with leading printer manufacturers[230]. Also service providers are important as they support industrial players in the acquisition of technological capabilities and relevant knowledge to operate AM. Melotte (BE) and Layerwise (BE) are two examples from Belgium. The most visible case remains however the one of Materialise who collaborated with Schunk (DE)[231] on a platform to produce and deliver AM gripper fingers that require particular geometries and of which most are no longer available in stocks (Schunk Greifer, 2015). In the **automotive** field, Volvo Truck (located in Rhône-Alpes, FR, and not SE), Koenigsegg (SE), BMW (DE), the Blok Group (NL), Concept Laser, Landré[232] (NL), Eriks (NL), and Carglass (FR) are exploring this issue (and some of them most likely already using) AM for spare parts. In the **equipment manufacturing** industry Sandvick Coromant (SE), SECO Tools (SE), AtlasCopCo and Mapal are developing applications already. Overall, specific cases can be found but also possibilities to order spare parts from platforms managed by companies such as shapeways, Sculpteo, Thingiverse. EOS (DE), Layerwise (BE, now 3DS), Materialise (BE) and Stratasys (IL/US) were identified as AM suppliers helping companies printing spare parts. This leads to the conclusion that from an AM supply point of view Western European regions are still on the forefront of this area together with American players.

225 However one should bear in mind the fact that the machine is expensive does not mean that the part(s) to be replaced will be more or less expensive.

226 Such as coolers for instance that require re-engineering costs.

227 See http://vil.be/

228 See http://www.mobility.siemens.com/mobility/global/en/services/spare-part-services/pages/spare-part-services.aspx

229 Nestlé (FR), Tetrapack (SE), Picanol (BE), Krones AG (DE), Wärtsilä (SE), COESIA Group (IT), from Emilia Romagna as well as Sacmi (IT)

230 Such as Trumpf (DE), Renishaw (UK), Concept laser (DE), SLM Solutions (DE), EOS (DE), Phenix Systems (now 3DS, FR), Fives (FR), ARCAM (SE), Realizer (holder of the SLM technology license together with FhG, DE) Stratasys (which is currently the only manufacturer of a multi-material and multi-color printer, US) but also producers of hybrid systems such as DMG MORI (JAP) and Mazak (JAP)

231 See http://www.schunk.com/schunk/schunk_websites/news/subject_of_the_month.html?article_id=25113&country=INT&lngCode=EN&lngCode2=EN

232 Source : http://additivemanufacturing.com/2015/08/03/concept-laser-additive-manufacturing-with-a-digital-process-chain-in-the-blok-group/

BARRIERS AND POLICY IMPLICATIONS. Parts such as water pumps, separators, air compressors, compellers and parts of forging machines would be of interest in the short term. Longer-term development tracks include the optimisation of spare part products already on the market. In the future, on-site hubs and metal workshops might be put in place, changing distribution patterns and eliminating or changing segments of the current value chain towards increased distribution. Designs could even be sold instead of parts. AM is therefore expected to reduce stocks and warehouses, deliveries (no shipping of the spare parts) and related environmental footprint, replacement/delivery times and wasted parts, and economic benefits resulting from distributed production that would counter balance its initial cost of adoption (Khajav et Al., 2013). Although no product-driven value chain could be identified, a missing capability was flagged by the research team: finishing and post-processing (see Box 17). It is indeed known the quality of AM is not sufficient (precision) to produce mechanical parts without using subtractive methods (polishing, etc.).

Box 17: Missing and/or under-developed capabilities in this value chain include...

- All the value chain is currently at an early stage of development: no clear supply chain could be identified beyond specific (and/or isolated) cases; However, finishing and post-processing capabilities remain to be developed (surface finition is key to this application area).

AM also remains expensive and sub-optimal compared to traditional manufacturing techniques and other barriers to its uptake follow: appropriate skills and curricula clearly come as a critical barrier together with the risk-avoiding culture of companies from the machinery sector. In addition, one should note that in case spares are available, AM is not needed. Available parts are therefore a hampering factor, as is the cost of AM which leads company managers to slow down their investments while expecting to see first returns before continuing to invest. Also, the need for a clear available distributed network of printers is conceptual at this stage. An issue to solve first would remain the one of designs availability which is linked to the warranty associated to the machine and to the replicability of the parts: why would a machine provider only sell its designs and lose production revenues? Finally, one should note that knowledge about AM materials and processes is clearly lacking. Differences between materials, printing conditions, as well as the lack of precision of AM are clearly obstacles. Policy implications can therefore be identified:

1. Knowledge should be developed and R&D conducted on all aspects of this area in order to reach a higher TRL level (closer to commercial deployment and applicable through direct R&D support, collaborative R&D projects, networks of infrastructures as well as one-stop shops).
    a. Materials and post-processing are key development areas under this heading.
    b. AM is to be further combined with subtractive methods, for instance in the form of hybrid systems which are already advanced in countries such as Japan.
    a. Collaborations should be promoted between the actors of the innovation quadruple (and why not quintuple[233]) helix[234]. These collaborations could be supported on key topics (whether business or purely R&D-oriented) and aim towards the development of hybrid systems.
2. Pilot production and demonstration facilities should be set up and supported to allow testing AM in this area. Support could emanate from:
    a. Regional and national authorities funding or supporting existing/new local facilities;
    b. The European Union to build upon and connect existing/new facilities at the level of the EU28.
3. Awareness should be raised among company managers through a dedicated website and appropriate events.

[233] See http://innovation-entrepreneurship.springeropen.com/articles/10.1186/2192-5372-1-2

[234] See https://ec.europa.eu/digital-single-market/en/open-innovation-20

4.2.7 Lighting and other home decoration products

CONTEXT. The AM of consumer and lifestyle products and in particular home decoration objects is only limited by size and materials possibilities. The application field under the scope is strongly associated to open sources[235]. A large number of designs including 3D data can be downloaded from 3D-printing community networks such as 3dhubs.com which enable each user at home to create own 3D-printed objects. Many hubs are even put in relation though the 3D Hubs network[236]. Europe shows a relative high share and level of density of these local hubs. The cities with most printers are New York (400), followed by Los Angeles, and followed by London which has currently more than 300 3D-printing locations[237]. Design and printing platforms enable consumers and designers to develop, produce, and sell their own products.

SCOPE. Examples of most important applications are art objects, vases, sculptures, wall décor, picture frames, furniture (e.g. chairs, tables), and particularly lamps. Personalization is a very strong issue in this field and 3D-printed products that is being explored by companies, designers, and customers themselves. The consumer market for 3D-printed home decoration products is however still a niche. Today, 3D-printing is less than 0,1% of conventional manufacturing in the total services and products made[238]. Due to Gartner's 2015 Hype Cycle report on 3D-printing, consumable products are the ones with the lowest level of expectation and are still in the stage of "*innovation trigger*". Still, the particularity of this value chain is that it allows for actively involving consumers develop, produce and sell their own products.

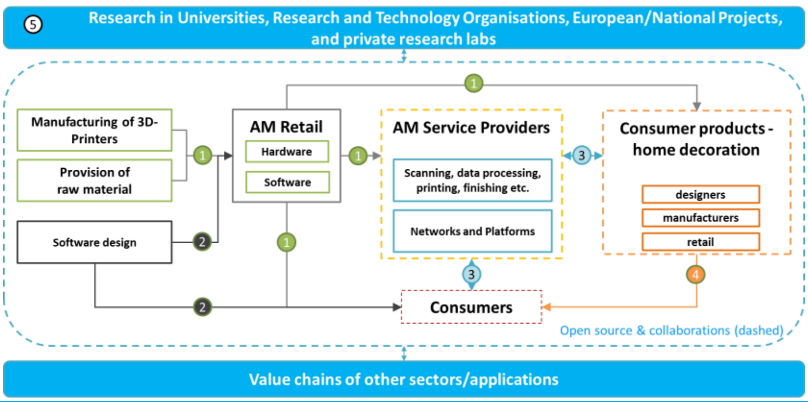
Figure 19: a) "Biophilia" and b) "Plüne Applique" lampshades of sintered polymer; and c&d) Stylized bulbs

Source (from left to right): Gässling, 2015, *http://www.gassling.com/*; and Exnovo, 2015, *http://www.exnovo-italia.com*

As the consumer printers are not yet fully deployed on the market, this application area is currently represented by artists and designers who create prototypes for galleries and small series of home products; as well as by networks and platforms for people to create and print their own (or downloaded) designs. Moreover it is clear that each of the 3D printed home decoration product types targeted by this case study only represent a very small application field and is not very mature from both technological and economic points of view[239]. Lighting products appear however to be the most advanced (and diffused) application in the market. These are usually made of polymers and/or composite materials. AM is valuable for lamps as it allows for new shapes and visual effects.

VALUE CHAIN. Despite of the well-known large companies involved in AM, few key players have been identified along the considered value chain. Most of the interviewed researchers and material or service providers do not exclude this topic and are willing to establish specific projects or to produce prototypes[240]. However, beside the well-know-companies, several (smaller) service suppliers and some research consortia, no key players were identified. This value chain is therefore fragmented and at an early stage. It should however be shaped by clear

Figure 20: Main segments of the additive manufacturing value chain for home decoration consumer products



235 See for instance Thingiverse, 2016, http://www.thingiverse.com/thing:19104/#files
236 See 3D Hubs (2016), "*3D-printing Trends*", available at https://www.3dhubs.com/trends which shows 25000 printers on the global platform of 3D Hubs, providing access to 3D-printing in over 150 countries.
237 Source: 3D Hubs "3D-printing Trends", January 2016, https://www.3dhubs.com/trends
238 See Antoine Blua (2013) "A New Industrial Revolution: The Brave New World Of 3D-printing", http://www.rferl.org/content/printing-3d-new-industrial-revolution/24949765.html
239 When regarding furniture AM applications for instance, only art objects, prototypes, and few design collections could be identified.
240 Sources: See list of conducted interviews in Annex 14.

drivers, such as the price of materials and technologies[241] on the consumer market. Only design collections and no mass products could be identified due to high printing costs and low printing qualities which makes surface treatments necessary. From the supply side, material providers [242] are active besides ink producers, such as Tiger and PV Nano Cell (working for example on single crystal conductive nano-inks). Main printer manufacturers[243] are international incumbents from both Western Europe and North America while a large number of AM service providers[244] from all countries are active in the area (though "key players" mainly originate from Western European regions). The value chain appears to be highly fragmented, mixing companies and end users who can have their say in the manufacturing of their home products. Customers can provide their own inputs to platforms and are able to sell their own design and print. Due to the fact that both companies and consumers are most likely to be active on this segment, one should note that both open-source[245] and more "classical" Software is being used in that area. The open character is quite important for this value chain: the sector is currently strongly driven by the user communities and new forms of IPR such as Creative Commons or GNU (Open Source Software) are of importance (still, traditional patents and industrial designs are also relevant) although they are not a barrier. Newcomers (e.g. users in platforms) nonetheless often need orientation and have to build up knowledge about the alternative form of licencing and protection (e.g. copyright, creative commons). Both open-source and more proprietary software is being used in that area. Relevant capabilities are available in Western European countries, Poland and the United States[246]. The disruptive effect of AM is here taking place at the level of the role of end users. Fab Labs are in that regard of main importance: 600 Fab Labs[247] (see Box 18) all across the world are offering 3D printing services to end users and one should in that respect mention Fab Lab Initiative[248] the Fab Lab Foundation[249].

Box 18: FabLabs and their concentration in Western Europe

Our analysis of the relative density of FabLabs in European regions with high end user involvement in 3d printing shows a concentration of existing FabLabs. The NUTS 1 level regions of NL2, NL, 3, NL 4, BE 1, BE 2, and DEA[250] shows a very high density and total number (more than 40) of Fab Labs. This also corresponds with the repartition of key players. The triangle between Milan, Turin, and Lugano also comprises twelve Fab Labs where efforts are mainly located around the larger cities[251]. The cities Monaco, Marseilles, Montpellier and Paris in France as well as Madrid, Bilbao, and especially Barcelona in Spain also show high density levels. Eastern Europe is not really involved in building Fab Labs.

Also internet platforms such as for example *3DHubs*[252] (NL, US) are key to the deployment of AM across the community. Some platforms are however linked to main players[253] willing to sell 3Dprinters and filaments to the broadest community possible. Mesh files can be downloaded and/or exchanged on these platforms. Besides the consumers, main actors on the demand side of the value chain are light products manufacturers, among which Philips (NL) is probably the most visible in Europe. A high number of manufacturers and vendors of home decoration products were identified being involved in the value chain as local resellers of the 3D printed design products. Designers or design companies are particularly important at this level of the value chain. They show their art pieces

241 At the moment the most common technologies and materials in the present application area are Fused Deposition Modeling (FDM) with the most common thermoplast materials ABS (Acrylnitril-Butadien-Styrol) and PLA (Polylactid) and Powder-based 3d printing Laser Sintering mainly with Polyamide (but also possibly with other materials, such as Alumide, Titanium, Rubber-like, and Wood).

242 Somos (DSM, NL), Evonik, EOS, and Lehmann & Voss (DE) and Arkema (FR), 3D Prima (Europe), ColorFabb (NL), cc-products (DE), DAS FILAMENT (DE), Dutch Filaments (NL), eMotion Tech (FR), Extrudr (FD3D GmbH) (AT), fabberworld (CH), Faberdashery (UK), FELIXprinters (NL), Filamentum (NL), iGo3D(DE), Innofil3D BV (NL), KDI Polymer Specialists Ltd. (UK), Nanovia (FR), Neofil3D (FR), Orbi-Tech GmbH (DE), Plastic2Print (NL), ultimaker (NL); other players are listed in Annex 13.

243 Including companies such as Stratasys including Makerbot and 3D Systems, EOS, SLM Solutions, German RepRap, or Voxeljet in Germany, Ultimaker in the Netherlands, and Zortrax in Poland.

244 These include among others Cirp, Profactor, Pinshape, Thingiverse by Makerbot, 3D Systems or Shapeways, Ponoko, Rapid 3D, Imaginarium, i.Materialise by Materialise, Sculpteo, Voxeljet and Alphacam.

245

246 With companies like Autodesk, 3D Systems, McNeel, Pixologic, and Pinshape, Materialise, EOS, Dassault Systèmes, Google (Google SketchUp) or MeshLab Printelize

247 As of September 2015 there were 107 Fab Labs in the US and Canada, and 270 in Europe (565 in the world in total). At the moment in Europe the countries with most established Fab Labs are Italy (64), France (58), Germany (31), The Netherland (28), and United Kingdom (23) – See https://www.fablabs.io/labs?locale=en.

248 See http://www.fabfoundation.org/fab-labs/

249 See http://www.fabfoundation.org/about-us/

250 Source: Eurostat (2013) Regions in the European Union, Nomenclature of territorial units for statistics NUTS 2013/EU-28; http://ec.europa.eu/eurostat/documents/3859598/6948381/KS-GQ-14-006-EN-N.pdf/b9ba3339-b121-4775-9991-d88e807628e3
NL2 = OOST-NEDERLAND, NL3 = WEST-NEDERLAND, NL4 = ZUID-NEDERLAND, BE1 = RÉGION DE BRUXELLES-CAPITALE/BRUSSELS HOOFDSTEDELIJK GEWEST, BE2 = VLAAMS GEWEST, DEA = NORDRHEIN-WESTFALEN

251 e.g. Venice, Verona, Padua, Modena, Bologna, Florence, Naples, and Rome

252 See https://www.3dhubs.com/

253 e.g. Thingiverse by Makerbot, belonging to Stratasys since 2013, U.S./Israel) and by service suppliers (e.g. Shapeways, founded in the Netherlands, now U.S.)

and prototypes at various art exhibitions or museums[254] or offer their exclusive, expensive, and often price-winning design collections in low volumes through online stores[255].
Also the service provider Materialise (BE) offers 3D-printed home decoration products within an online shop, called .MGX by Materialise[256]. Exnovo and Materialise have established global networks of local distributors and resellers of their design collections.

Still, the market is currently not shaped for mass production but rather for high-end products, partly driven also by user communities and platforms. This is among other things due to the lack of performance and the non-advantageous costs of 3D-Printers on the market. If no particular capability is currently missing in Europe (whether at the hardware or software level – see Box 19), it is clear that these capabilities are not bundled and would benefit from cross-fertilization. Players are not equally distributed over the European territory and are mainly concentrated in Western European countries such as Belgium, the Netherlands, Sweden, Germany, France, Italy, and the UK, but also some successful players in Eastern Europe were identified, e.g. in Poland and Slovakia. In Europe most visible key players come from Belgium, the Netherlands, Germany, United Kingdom, Sweden, and France. Eastern European companies are part of the value chain, however, only few companies have substantial size already such as in Poland[257] or to a more limited extent Czech Republic and Latvia. From a 3D-Printing capabilities' point of view, developments seem to be steered by large US-based firms.

Box 19: Missing and/or under-developed capabilities in this value chain include...

- Although they are to develop, no particular capability appeared to be missing in this value chain – existing capabilities however remain to be bundled.

BARRIERS AND POLICY IMPLICATIONS. Technological improvements are therefore still expected: production time, finishing, quality, toxicity, stress testing, costs and other technical parameters are not yet optimal. Among the emerging areas, combinations of new lighting technologies with sophisticated 3D printing technologies (4D printing) are now being explored by research labs and companies. Philips has for example developed smart home applications for lightings, some of which are already 3d printed[258]. Research[259] is existent but the topic is not seen as a main priority. New materials (incl. ink materials) and multi-material printing (segment led by Stratasys, IL). 4D-Printing is particularly promising but at a basic research stage. Among the barriers to the uptake and development of 3D-Printing in this area, technological improvement is to be mentioned as well as the need todevelop materials and processes (incl. 4D-Printing). Particular barriers can even be identified that apply to Eastern European regions[260]: the fact that the market is small and dedicated to expensive designer products; the fact that only few key players are active in this area; missing knowledge about 3D-printing; and the fact that the consumption remains at a very low level. Awareness and quality information are also missing and hamper the uptake of 3D-Printing in this area. Policy implications can be synthesised as follows:

1. Supporting technological advancements and future innovations: Home decoration consumer products still have low expectations and need further innovation efforts to enter the market at a larger scale. Printing qualities are still not sufficient for small objects and products often need further surface treatments after printing. Long production time is a limiting factor. Technological advancements, e.g. 4D printing, which will be delivering definable and varying material qualities, including electronic qualities, within one printed object, will open potential application fields for consumer products, especially for lighting products. For user-dirven 3D-printing, advancement of printing technologies or new innovations are also needed otherwise consumer 3D-printing might become disillusioned in the future. AM technical limitations and missing knowledge imply that further R&D has to be conducted with relevant co-investments from the public sector (at regional, national and EU levels) for areas such as:
   - AM processes;
   - Material properties;
   - Quality monitoring, control and detection systems;
   - Toxicity, explosivity and broader health impacts of used materials;
   - Reduction of production time and cost.
2. Supporting specific regional collaborations: Potential key regions with high concentrations of involved end users and vendors of 3D-printed home decoration products were identified (e.g. Netherlands/Nordrhein-

254 See for example the ONE_SHOT_MGX. which is a foldable stool manufactured by selective laser sintering as one complete piece. https://mgxbymaterialise.com/principal-collection/interior/families/mgxmodel/detail/detail/45; for more examples see e.g. https://mgxbymaterialise.com/limited-editions/mgxmodel/list/list

255 e.g. Freedom Of Creation (FOC) by 3D Systems in the United States, Purmundus by Cirp and Shape and Form in Germany or Exnovo in Italy.

256 See https://mgxbymaterialise.com/

257 There are several printer manufacturers (Zortrax, Monkeyfab, 3DGence, Tytan3D) and distributors (Get3D, CadXpert, Printila) in Poland – see https://3dprint.com/34332/cd3d-best-3d-printing-2014/

258 Source: Harpe J. (2014) "Light, Art and hue: Unleashing the beauty of light with Philips Hue 3D-printed luminaires", http://www.newscenter.philips.com/main/standard/news/press/2014/20140328-unleashing-the-beauty-of-light-with-philips-3d-printed-hue-luminaires.wpd#.VrB5_E32bVh

259 Performed by RTOs such as the Fraunhofer Institute for Laser Technology (ILT) and RWTH Aachen University.

260 Sources: http://3dprintingindustry.com; Fab Lab Foundation (2016); http://www.fabfoundation.org/fab-labs/

Westfalen, in Italy, South France, and in Spain). Networking activities, knowledge exchange platforms, and other actions could support local players and raise common awareness.

3. Supporting user platforms: Regarding the relatively high involvement of European users (see e.g. Fab Labs or 3D Hubs) within 3D-printing platforms, specific opportunities for Europe could be supported financially and with specific actions, e.g. establishing initiatives such as Fab Labs, especially in Eastern European countries. Although many customers do not yet demand highly individualized products small user groups and communities serving as lead uers might enable a broader development spreading to various submarkets.
4. Development of testing, finishing, post-treatment and demonstration capabilities. These capabilities could be networked accross regions involved in the different areas under the scope from research to commercialisation, involving RTOs, companies, etc.
5. IPR helpdesks and IPR support from the public should also cover new forms of IPR such as creative commons, rules concerning open source software development, etc.
6. Creating new curricula on 3D-printing: Generating knowledge and raising awareness on AM process, materials, applications, and actors, especially in Eastern Europe.
7. Supporting prototypes and experiments: So far, designer prototypes for new applications are rather expensive and have to be financed by the small design conpanies or single designers in most cases. Supporting the development, production, and systematic testing of prototypes in new application areas of consumer products for home decoration, as e.g. surface elements for wall decoration, could help to reduce innovation barriers.

4.2.8 3D-printed textiles

CONTEXT. In technical textiles, 3D printing[261] has already been used to create applications such as flexible heating systems or wearable technology. In design garments such as bikinis, complete dresses or shoes are 3D printed. These garments, however, are clearly produced for show and demonstration, not for everyday wearing[262]. Applications focus on the combination of 3D printed elements with textiles, e.g. as for shoes, where the sole is printed and then fixed to the upper part. AM is currently not able to replace conventional fiber-based textile production yet and can still be regarded as a small market for designers (with the exception of Tamicare). Markets include the high-performance textile market, the smart or intelligent textile market as well as customised sportswear or protective clothing. Industrial textiles with special drapings or hooks for e.g. curtains or buildings are another possible application area.

SCOPE. For application of 3D printing of textile one has to distinguish between *3D printing of textile s*tructures on the one hand and the combination of textile material with 3D printed items on the other hand, being either directly printed on the textile or bonded with it by other matters e.g. agglutination. Key applications fall under the category of consumer products (clothing, shoes and accessories) and textiles where (smart) components will be printed on or combined with textile material using AM methods (direct printing on textile materials) or are a combination of production techniques (e.g. sports shoes or protective clothing). 3D printing on textiles to add additional features and functional structures offers interesting possibilities for customized production, important for instance for protective clothing or sportswear. The scope of the case was therefore focused on the segment of textile printing and design as well on manufacturing shoes and protective clothing (see Figure 21 for example). This area is also among the most mature ones in the field of 3D-Printed textiles.

Figure 21: Futurecraft 3D by Adidas and Materialise

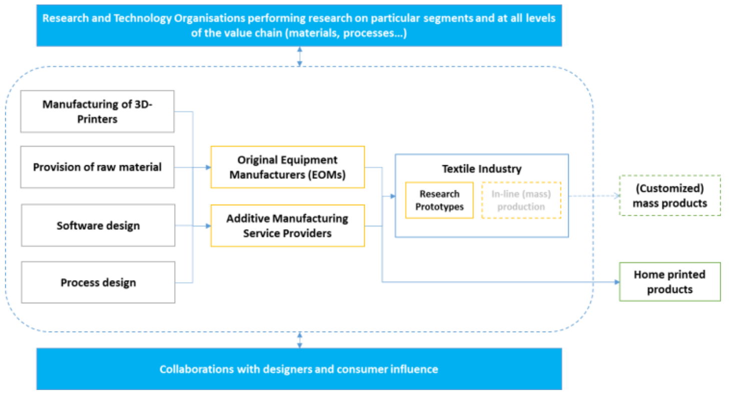
Source: http://www.materialise.com/cases/adidas-futurecraft-the-ultimate-3d-printed-personalized-shoe

[261] Despite its low resolution level, Fused Deposition Modelling is the most inexpensive method and furthest developed for private use or small companies, it is the method most often used for direct 3D printing on textiles. Polymers such as natural latex, silicone, polyurethane (PU) and polytetrafluoroethylene (PTFE), as well as a range of textile fibres, such as cotton, viscose and polyamide (PA), can be used as well as other materials depending on the specific application

[262] see Melnikova, R. et al., (2014).

Shoes manufacturing for instance falls under the scope of this area and is a labour-intensive business but also a matter of designers[263] and artists. As shoe technologies continue to evolve, particularly athletic shoe designs, the number of shoe pieces added together has increased, requiring increasingly complicated manufacturing steps to produce shoes[264]. Customised textile production is also important in the production of protective clothing and sportswear. Cross-value chain applications[265] are also emerging: two examples are technical (smart and electronic such as wearable sensors) textiles[266] and protective clothing which can be found in the sector of medical devices, where support structures can be printed out fitting the patient´s individual needs[267]. Pervasive features such as flexibility, low cost, robustness, unobtrusiveness, washability, small size, biocompatibility with human skin, and aesthetic sense are important requirements for the electronic textiles.[268] So far systems include direct print onto textile materials in combination with traditional means of connection[269], like stitching of electronic devices onto textile material or weaving of conductive threats into fabrics. Most printing processes concentrate on one electronic component, such as printing of batteries or antennae, and combine the different elements by traditional methods with connecting wires or, on the other hand, stitch complex devices, such as batteries or sensors, onto textile material in combination of printing connections between them with conductive inks or pastes. The printing of textile structures remains at present at a level of research or fashion design resulting in very rigid materials connected through hinges or mimicking kinematic structures[270]. Direct 3D printing on textiles to add functional parts on the other side is not that far developed and results mostly in research prototypes.

Figure 22: Main segments of the value chain of 3D Printing & Textiles



Source: Own depiction, 2016

VALUE CHAIN. Many companies are involved in this area, including Adidas (DE), Nike (US), New Balance (US), and other classical incumbents. But in general, all applications in the textile sector as analysed in this case study are still in development stage or just in the market introduction stage, currently they address very specific and rather narrow high-end markets. Only niche and designer products are on the market and can be printed at home, while mass production of textiles or textiles in combination with 3D printed parts still awaits the successful implementation in the production process. However, at present 3D printing seems to have a breakthrough in shoe industry, as shoe technologies continue to evolve the number of shoe pieces added together has increased, requiring increasingly complicated manufacturing steps to produce shoes. Laser Sintering techniques are used in that respect.

263 Examples include Iris van Herpen, Earl Stewart, Katrien Herdewyn, Troy Nachtigall, Pauline van Dongen & Leonie Tenthof van Noorden.

264 US-patent US 9155357B2 "Automated Strobel Printing"

265 Health monitoring of vital signs of the wearer such as heart rate, respiration rate, temperature, activity, and posture; Customized ortheses/prostheses; Sports training data acquisition; Monitoring personnel handling hazardous materials - Sensors integrated into clothing as part of personal safety applications; Tracking the position and status of soldiers in action; Monitoring pilot or truck driver fatigue; Textile RFID transponders for logistics or for anti-theft and anti-fraud protection in clothing; Large-area fabric with integrated sensors for alarm systems; Innovative Fashion (wearable technology); Textile keyboards or switches; Increasing safety through lighting and displays on and in fabric ; Regain sensory perception that was previously lost by accident or birth.

266 Smart textiles can overall be defined by their ability to sense stimuli from the environment and have the inherent capability to react and adapt to them by the integration of functionalities within the textile structure. Electronic textiles describe the convergence of electronics and textiles into fabrics, which are able to sense, compute, communicate and actuate. In combination with electronic textiles this provides a vast field of application for emergency personnel, such as firemen, police or ambulance, as well as for leisure applications, like functional bike gear, mountaineering and other sports.

267 In combination with padding textile materials they give the right support while providing the accuracy and comfort needed for some cases.

268 Kim et al 2009

269 Conductive materials, that are printable and stretchable, have been developed in order to meet demands of both conductivity and flexibility for electronic textiles.

270 See http://n-e-r-v-o-u-s.com/projects/sets/kinematics-dress/

3D printing can help to shorten some steps in the production process. 3D scanning can be used to design individual 3D models of each customer. These modes can either be printed out as full size dress forms or used as virtual model to connect to individual 2D textile cuts[271]. Home desktop printers are offered from various companies worldwide, with a strong market in US and China, but also a lot of upcoming companies in Europe. Well-known companies such as 3D Systems (US), Stratasys (IL), EOS (DE) or Materialise (BE) are key players in the textile sector as well. On the side of material development there are also some new and specific companies such as Recreus (Spain), Plastics2print, Colorfabb (NL) and Tamicare (UK). Materials range from elastomeric materials to rigid or conductive materials, depending on the intended use. A lot of small start-up companies in the US and Europe, especially the Netherlands, are developing new materials that are available over the internet. However, these companies are far from being profitable yet. New business models have to be considered to help that these companies become established on the market. Examples for such small business companies or inventors are Colorfabb; CC-Products; plastics2print; or Recreus[272], a more comprehensive list of suppliers, if not inventors is given on the RepRap homepage[273]. Original Equipment Manufacturers (OEMs) cooperate with service providers and printer manufacturers such as Materialise (BE), cubify (now 3D Systems, US) or Stratasys (IL). Some of the AM service providers own platforms from which designs can be downloaded (e.g. cubify, shapeways, aoku, thingyverse, mgxbymaterialise).

As 3D-printing also entails opportunities for smart textiles, e.g. for medical applications, consumer products or various safety applications. In combinations with 3D-printed conductive materials, it will open a market for directly printed smart three dimensional functionalities on textiles. Companies with products close to the market or already on the market come from the UK, Germany or Finland. A lot of research is conducted in European research institutions, as it is the knowledge on possible material combinations and printing conditions that can make European industry leading in the section of textile processing (e.g. Sächsisches Textilforschungsinsitut STFI (DE), Textilforschung Thüringen (DE), Centexbel (BE), Saxion (NL), Fraunhofer Insitutes (DE) and others).[274] Also the use of recycled and biodegradable materials, and bonding between the textile and the printed item (either through agglutination or direct printing on textile surfaces). Personalization is the upcoming trend in shoe design and printing of individual parts[275]. Research[276] is also going on within Europe on key topics such as printing conditions or materials (or combinations of both). One of them concerns the combination of 3D printing with conventionally produced textiles and in particular bonding effects between the different materials and constraints it should resist[277]. A second issue regards 3D-Printing as a process that is not in-line yet. Other areas include more suitable filament materials; Developments in CAD software and hardware; Research into adhesion between 3D printed material and substrate (textile material); Development and integration of technology into in-line production processes; Linking design and end user need; and Smart and functional textiles. Looking at the regional dimension of the case study we can observe that the value chain and relationships between the various players are just emerging.

At the moment, we cannot identify any key region or cluster where 3DP applications related relationships are of significant importance. However, European research institutes play a strong role in development of knowhow concerning 3D printing on textiles and development of electronic textiles, where Asian research has also a strong impact. Companies in the UK, Belgium, the Netherlands and Germany (whether new firms or incumbents) might also become key players in the field. Research institutes in Belgium, the Netherlands, the UK, and Germany are most outstanding, for research in electronic textiles also in Italy. Companies with functional textile products close to the market or already on the market come from the UK, Germany or Finland. Regarding Eastern Europe no relevant key players in the value chain of 3d printing of textile consumer products could be identified.

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271 Software for this is developed e.g. at the Hohenstein Institute in Germany – See http://www.hohenstein.de/en/inline/projectdetail.xhtml?researchProjectFilter.file=%2fmedia%2fforschungsprojekte%2fVirtuelle_3D_Modelle_IGF_18223BG.xml&applicationArea=283

272 http://colorfabb.com/
Inventors like http://cc-products.de/ products are available through https://www.matterhackers.com/store/3d-printer-filament/poro-lay-lay-fomm-filament-175mm
http://www.plastic2print.com/
http://recreus.com/en/

273 http://reprap.org/wiki/Printing_Material_Suppliers or http://3dplatform.com/top-10-new-3d-printing-materials-you-should-try-part-i/

274 e.g. Sächsisches Textilforschungsinsitut STFI (DE), Textilforschung Thüringen (DE), Centexbel (BE), Saxion (NL), Fraunhofer Insitutes (DE) and others

275 US company Sols is producing 3D printed custom insoles, that can be ordered online by simply following easy instructions of an app and uploading pictures of each foot

276 Entities include the following: Brunel University in Surrey (UK); Center for Micro-Bio Based Robotics of Instituto di Tecnologia (Italy) Dublin University (Ireland) Fraunhofer IZM (Germany) Fraunhofer IWS (Germany) Infineon (Germany) Insituto Italiano di Tecnologia – Center for Space Human Robotics (Italy) Patria (Finland) Philips research Laboratory (UK) Politecnico di torino, Politronica Inkjet Printing S.r.l. (Italy) Saxion University of Applied Sciences Enschede (The Netherlands) Tampere University of Technology (Finland) University Bolton (UK) University Ghent (The Netherlands) University of Southampton (UK) Wearable Technology Ltd. (based in UK, production in China)

277 Which is achieved through combination of materials and printing parameters or by simply gluing the 3D object to textile structures. The functionality of the added item has to be maintained throughout the lifetime of the textile, despite repeated washing, drying cycles or mechanical stress.

BARRIERS AND POLICY IMPLICATIONS. Main barriers slow down the development of this area. A key barrier is hence the lack of technological knowledge about how to industrialise 3D printing technologies integrating 3D printing in very fast in-line processes of the textile industry. A key barrier is hence the lack of technological knowledge about how to industrialise 3D printing technologies integrating 3D printing in very fast in-line processes of the textile industry. It relates to key missing capabilities in the area (see Box 20). This holds true for all applications expect for printing of (in)soles for shoes and protective equipment where the development is already more advanced and the barrier is rather a business policy issue (e.g. market strategies, business models). Concerning printing textile-like patterns the limiting factor at present is on the one hand insufficient mechanical properties of pure printed 3D products, when compared to products derived from common technologies such as weaving or knitting. On the other hand the fact that textile CAD data for the creation of textiles produced through additive manufacturing needs to be adapted to the applications. In addition, 3D printing faces the boundaries that when mimicking textile structures like woven or knitted fabric the space between the single "threads" need to be distinct so that a moveable structure is obtained. Thus the limitation is the resolution of the 3D printers. Also the need to increase understanding of new reliable materials including better simulation and software stands as a barrier. New production systems with linked 3D-Printing and traditional technologies and data systems/interfaces to achieve highly integrated and combined technologies also need to be developed, and in-line printing of functional parts on textile material should be achieved in order to make processes more productive. There is a lack of common research and interactions between key players, as well as a concentration of supply capabilities in Western European regions. Knowledge is still missing regarding 3D-printing materials and processes. These are limited in terms of performance (size of the product, printing length, costs are among the main barriers from that perspective).

Missing capabilities were also spotted during the research such as presented in Box 20, mainly in terms of materials (from elastomeric materials to rigid or conductive materials) and finishing. An opportunity however stands there as start-ups in the US and Europe (especially the Netherlands) are developing new materials that are available over the internet. But they require new business models to become profitable. Moreover, engineering grade material selection is limited compared to conventional manufacturing and 3D-Printed products are not strong enough and concerned with surface roughness and the lack of sufficient resolution of 3D-Printers (which translates a need for sufficient distances between structures to create woven or knitted-like structures. Policy implications were derived from these observations. Some of them are broad, such as the fact that in order to support start-ups within this value chain, user-oriented initiatives with open source character should be promoted (such as e.g. Fab Labs or 3D Hubs, as described in the previous application field).

Box 20: Missing and/or under-developed capabilities in this value chain include...

- Software and simulation capabilities can be further developed;
- Adapted systems (in view of in-line production), incl. relevant interfaces;
- The landscape remains scattered;
- New (elastomeric, rigid, conductive, etc.) materials.

More specific implications can be described as follows:

1. Co-investment in R&D is needed to advance key fields (recycled materials, health impacts, cellulose fibres, etc.). In particular, there is a need to increase understanding of new reliable materials including better simulation and software, specifically software that allows the simulation of how the product will react after curing or melting with different materials. A more common baseline for comparability in tests between different materials and machines is also necessary. A focus must be laid on the industrialisation of 3D-Printing technologies, for instance the development of new production systems with linked 3D-Printing and traditional technologies and data systems/interfaces to achieve highly integrated and combined technologies. Crucial point to bring 3D-Printing into textile industry will be the achievement of in-line printing of functional parts on textile material, in order to make processes more productive. In combination with principles like Cyber-Physical Systems and the Internet of Things personalized production may become reality even for textile industry, printing functional, individual elements on textiles or combining 3D-printed parts like soles with textile elements to create customized itemsTopics of the research agenda encompasses:
    a. AM processes, esp. resolution of 3D-Printed parts;
    b. Materials selection, materials properties including health impacts (esp. also recycled materials, such as cellulose fibres);
    c. Quality monitoring, control and detection systems;
    d. High-performance and high-volume production;
    e. Printing cost reduction.
2. Consequently, collaborations should be supported, especially between research institutes and textile industry. In order to promote applications in this field collaborations within the value chain should be supported. Especially collaborations between research institutes and textile industry, and also with 3D-printing end users, including 3D-printing communities. In addition, opportunities emrge in suing textiles in other industries such as automotive and aircrafts, hence there are cross-sectoral collaboration opportunities. Electronic textiles offere a huge opportunity as well, however, these appllications where not in focus of the case study on specific value chains.

3. The development of new business models should be supported. This is escpecially relevant for the alreaedy further advanced applications in the shoe and protective clothing area where the specifics of the individualisations can alreadxy be exploited as it adresses existent customer needs.
4. Activities supporting the involvement of users should have an open source character. In collaborations with RTOs, clear contracts have to be signed to ensure IPR protection. Supporting and supplying information to SMEs regarding the protection possibilities for their designs would be beneficial together with support in case of SME IPR infringement.
5. New curricula (regional and national levels are here concerned but the EC could still take a coordination role here) should be developed in order to foster the diffusion of relevant skills among the EU workforce;
6. Finally, platforms and networks for consumer participation should be strengthened a strong driver for the development are users which can pull the development and form a critical mass which finally could facilitate the formation of larger markets.

4.2.9 Affordable houses

CONTEXT. The use of Additive technologies in the construction sector is recent. Large-scale 3D printing, such as ‘mega-techniques’, is becoming more and more relevant especially since 29 March 2014 when work began on the world’s first 3D printing house (Wainwright 2014). However, Perkins & Skitmore underline (2015) that it is not yet fully clear which role 3D printing currently plays in the construction industry and where this technique could be heading towards the future. The area is currently at a research and prototyping stage. It is estimated that a real market for 3DP in construction will only appear in 5 to 10 years. A key limitation is here the conservative nature of the construction sector and its overall reluctance to innovate. The construction sector often consists of many smaller suppliers and overall R&D budgets are limited compared to other sectors. Another challenge is that the construction of houses is based on components that require multi performative and multimode operations, which implies complex settings that require more than the sole development and use of AM techniques.

SCOPE. The use of AM in construction is at an early stage. No mature applications exist yet and value chain and markets are still to be established. This application area was studied because of its potential high positive impact on the reduction of green gases due to more efficient production techniques implying a productivity rise for the entire construction industry. Among other parameters, the construction sector also has a broader outreach potential to other sectors such as aerospace, defense and offshore. Four broad potential application areas where AM can cross-fertilize the construction sector[278]. At this early stage, it was decided to emphasize a set of products for which experts have expressed a high probability for future markets to develop: the application area under investigation will be affordable houses (see Figure *23*). Indeed, AM is currently being tested to manufacture future 3DP houses and temporary buildings (like pavilions for festivals that only stand for a few days/weeks - or shelter in disaster areas), custom made interiors or building details.

Figure 23: Illustrative applications of 3DP houses from the Chinese player Winsun

Source: http://factor-tech.com/3d-printing/3421-are-3d-printed-houses-practical-the-experts-weigh-in/

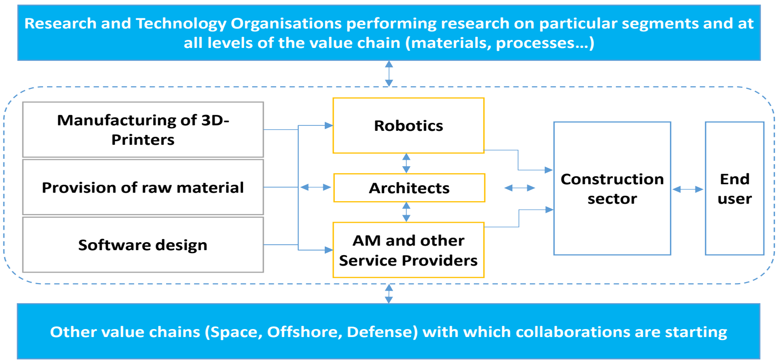
Different materials and AM technologies are being used to make entire buildings, building components or furnishings for buildings. Here the use of AM renders constructions more sustainable, less expensive, stronger, smarter, recyclable, and customizable to the environment. AM is associated both to functional and non-functional parts and especially to the design and is seen as key to better integrate house components. One has to distinguish between three techniques based on the size of the object used. Printing entire buildings requires new AM solutions such as very large printers that can either produce large pieces that can be assembled into bigger structures or come up

[278] (1) Design application and structural Engineering advices such as the familiar models use by architects to illustrate their design; (2) Material related advices and supports such as the structural engineers of the global design and engineering consultancy ARUP looking at AM to optimize construction steelwork applications in a variety of complex buildings; (3) Mechanical equipment related advices and supports; (4) Construction manufacturing. Source: http://www.freeformconstruction.com/partners.php

with entire units such as rooms or houses. Big printers[279] are often concrete printers that do not yet integrate steel bars. Another solution is the combination of robotics and AM technology, which is used when the pieces are bigger than the printers. In terms of future value chain development this cross-over between construction, AM and robotics is a highly important evolution. Most AM materials for construction use can be divided into three categories: plastics, concrete and metal. Next to cement and plastic, also other materials are being experimented with such as cellulose or even salt. Full-scale 3D prints of cellulose- based material show the cross over between forest industry, construction and AM. Because of safety reasons plastic houses will not be accepted by regulation. Most of the activities that relate to building houses have focused on printers that use concrete. The most popular building printing technology has been the USA based contour crafting launched almost 20 years ago. Most advanced technologies focus on the scale up of metal structures for the construction sector at the moment.

VALUE CHAIN.

Figure 24: Main segments of the injection molds additive manufacturing value chain



AM for affordable housing won't be subject to clear value chain segments until it emerges in 5 to 10 years, but some European RTOs research the topic intensively by investigating material, printer, robotics or construction. The first start-ups have just been created in the field and most promising ones already attracted the attention of overseas investors. Some key projects could be identified during the case study research as well such as in the Netherlands, in the UK and to some extent other Western European countries (Germany, Italy, etc.) but of course also internationally (the US but also China which is contributing to advancing this field). Companies in the sector remain reluctant to adopt and test the technology, with the exception of Heijmans from the Netherlands and SKANSKA from Sweden. Most actors involved in the additive manufacturing of affordable houses are located in the Netherlands (North Holland, South Holland, North Brabant, Utrecht), the UK (London, North-West England, West-Midlands, East Midlands, South-East England), Germany (Bavaria, Hessen, Baden-Württemberg, Rheinland-Palatinate, Nordrhein-Westfalen) and Switzerland (Zürich). Key players are also located in Italy (Tuscany), Sweden (Västerbotten, Skåne), Belgium (Flanders) and Finland (Uusimaa, South-Carelia). Other specialized companies working on AM in areas such as Offshore, Defense and Space sectors might also lead to spill-overs to the construction sector and collaborations exist across value chains[280]. From an international perspective, leading players in the field are Singapore, Switzerland and the USA. EU countries are lagging behind and research activities are reduced to a few players. Some significant activities are concentrated in the UK (London, North-West England, West-Midlands, East Midlands, South-East England), Northern Europe (Skåne, Västerbotten) as well as in Italy and Spain (Catalonia in particular). However, the most important work in Europe has been concentrated in and around ETHZ (Zürich, Switzerland). It was striking that no activities and capabilities exist in Eastern European countries with the exception of the concrete printers built by BetAbram in Slovenia (see Box 21).

Almost all activities observed are "*pure*" research or in some cases applied research in collaboration with the industry. Several collaboration agreements with RTOs can be identified in the area of additive manufacturing for construction. Some are clearly in a lead position in Europe, such as ETHZ as they collaborate with the private sector on strategic research[281]. Among the topics investigated, the most popular seem to touch upon how AM, robotics and automation can change the way things are done in the construction sector. Though all the research teams have the same objective, the teams are investigating very different materials and fabrication methods. For the construction of mega components or entire structures there is a new trend to investigate the use of robots and automation. The line between printers and robots is thin, so they were treated separately[282]. Robotics are already

279 The large scale printers used to produce big pieces can be large scale cement 3D printers using a system of extruding wet cement through a nozzle. In addition powder-based 3D-printed cement structures can be made by mixing polymers with cement and fibers to produce very strong, lightweight, high-resolution parts on readily available equipment (UC Berkeley College of Environmental Design).

280 For instance, the D-Shape concept from Monolite UK Ltd has gotten attention from Areospace research and industry.

281 Other key entities include TNO, VTT, TU Delft, TU Eindhoven, University of Darmstadt, Umeå University, Lund University, IAAC, and ETHZ

282 In Europe most important printer/robot projects are D-Shape of the firm Monolite (Tuscany [IT] and London [UK]) , 3DCP (East Midlands [UK]), and MX3D (Noord-Holand [NL]) while from the US the Contour Crafting technology is seen as important (California, USA). Other interesting European printer projects are KamerMaker (DUS Architects and Ultimaker, NL),

playing a key role in the development of the construction sector. Key players from the industrial robotics industry that have been active in the construction field are KUKA from Germany and ABB from Switzerland. In addition Stäubli from Switzerland and to a lesser degree Comau from Italy and Fanuc from Japan have worked on robots for the construction industry. Architects remain key to the area[283]. Also some US players such as the Jenny Sabin Studio and Kushner Studios have contributed to this field. All are able to shape up complex designs, which is of particular importance in this case as software is expected to become a key added value segment. In Europe new software development in the field happens either at universities or at spin-offs (for example ROB Technologies AG in CH) and start-ups (for example MX3D in NL). A trend here is that big software players from the USA are buying promising European start-ups. In example of this overseas acquisition strategy is WithinLab from the UK that was bought by Autodesk. Other big players in the field have been Materialise from Belgium. As software offers the platform for value creation these acquisitions are not a priori positive for Europe. Software plays a key role in the research projects. MX3D stated for example that 70% of their activities consists in software. Another segment gathers AM service providers who have worked for the European construction sector in this field are Materialise (BE), 3D Systems (USA)[284] and EOS (DE). The 3D-printing service providers collaborate with Architects. Other service providers have been based in the UK, such as Shotcrete Services Ltd. (concrete spraying solutions) and Buchan concrete Solutions and Bureau Happold. They may also be part of the value chain with the construction sector category. These companies collaborate with the construction sector, from which only a few firms committed to research projects on 3DP such Heijmans (NL) and Skanska (SE).

Box 21: Missing and/or under-developed capabilities in this value chain include...

- Overall the 3DP activities related to affordable housing are scattered over Europe with only few countries and some of their regions that do well such as the Netherlands and the UK. To reach critical mass it would be beneficial to bundle forces. Eastern-Europe seems not to have activities in this field apart from some SMEs activities from Slovenia. A majority of the most important activities seem to be concentrated in Western Europe (German speaking regions for material development and robotics, UK and the Netherlands). One additional missing capability is not technological but relates to the financing and ownership strategies of promising ventures especially in the fields of design and software development. It seems that the continuity of European ownership is not always realized in this field what may potentially hamper optimal growth of the company targets and their European ecosystems. Furthermore even and especially in countries that are active in the field there seems to be a need for 'bridging people' that understand robotics, software and the construction sector as to make development projects more successful.

BARRIERS AND POLICY IMPLICATIONS. AM technology will disrupt the construction landscape but remains in its infancy (which partly explains why IPR were not spotted as a current issue, although massive acquisitions from foreign players make it a risk for European ones). Two phases are foreseen in the uptake of 3DP by the construction sector: (1) in the mid-term some parts of houses will be made via 3DP, (2) in the long term one could think of integrated multi-mode methods using different materials, 3DP and new techniques. One of the benefits will be that planning mistakes will be corrected for thanks to AM and the efforts will shift from construction to planning. This will most likely come together with co-creation with customers and mass production. It can be expected that the construction value chain will take on board new players which are companies specializing in additive manufacturing and robotics. In addition the role of the users will be more pronounced. Other trends can be observed, such as the shift towards a holistic view to buildings. This trend goes beyond the construction as digitization is striving many sectors to new modes of building and production. Another key trend is the fact that online applications will appear where clients can customize their houses. New business model could appear where people can order new doors or new colors for their house even by paying monthly fees or membership money. A third key trend is that in the European economic downturn some construction companies driven by the search for value added realized that they will be forced to innovate to remain competitive. A last trend is that engineering consultancy companies (who are key players in this value chain) picked up on the use of digital design with practices such as parametric design and optimization. Material providers are usually large companies from bigger countries such as Germany (such as Henkel and BASF) and UK (LaFarge Tarmac). Materials, such as concrete, tarmac, wood and steel – entailing concrete spraying, resins and (bio) plastics (provided by companies such as Henkel) and metal powders and welding material (provided by companies such as Arcelor Mittal). Key players also look into new innovative solutions (see for example G.tecz Engineering GmbH). Some experts foresee that materials are going to be customized, meaning that all parts of the system are changing. Material will be prepared and transformed according to the user needs and required performance. Customization is starting from material to process and product eventually but further research will be needed – on processes and materials but also customization practices– to lead to effects.

TU Eindhoven and ROHACO concrete printer (NL) , Betabram (SI) and some (conceptual) projects at IAAC (Catalonia, Spain) and ETHZ (Zürich, Switzerland) and the printing heads/systems of .G.tecz Engineering GmbH (DE).

283 People at IAAC in Spain, at architect practices in London and at the ETHZ in Zürich are important to mention here.

284 Players such as Z Corp (USA) and CRDM (UK) have recently been bought by 3D Systems . In addition Emerging Objects (US) has been a key player, especially in the US.

Obstacles to the uptake of AM remain, some of which are linked to the limitations of current robotics and printers who do not offer part integration, multiperformative and multimode operations. The first challenge relates the production of components in pre-fabrication. For pre-fabrication a computerized assembly line is needed that is easy to automate. For this pre-formation stage light materials such as wood are preferred as they are easier to transport then for example concrete. One should note that the size, volume and cost of AM are not yet satisfactory compared to traditional technologies. The second challenge relates to onsite construction. On site construction requires on site robotics interacting with humans, which implies complexity. Another key challenge for the field is that materials should still be developed that can be processed on printers or contour crafting machines and that can fit the requirement of the building industry. Scaling up remains a challenge as because buildings are not small objects. Also the speed of digital manufacturing in both AM and robotics is not satisfactory. Cultural changes and an improvement of skills are clearly needed to open the sector to AM. In addition to a paradigm shift (which also concerns architects), more cooperation is needed between different fields The sector is highly conservative and risk-avoiding and is not yet fully multi-disciplinary. This is problematic as there is a need for coordination and bundling forces as to speed up the research and commercialisation process. People involved in construction activities also doubt about the sustainability of AM products. Awareness about AM is therefore missing. Standardisation and building but also safety regulations are aso obstacles to AM which should comply with a number of standards.

That also comes with IPR issues and a creative entrepreneurship[285] culture that is somehow lagging behind compared to other sectors. Policy implications derived from those observations are that framework conditions and awareness could be improved by public entities. Additional implications are the following:

1. Education and training policies should strive toward multi-disciplinarity (mixing robotics, software and construction, with particular emphasis on design and software development).
2. policy should focus on the creation of platforms and ecosystems that can create the value which is usually to be found around new firms.
3. Coordination is needed in such a scattered landscape to invest in technology.
4. More ambitious financing programs are a condition for more ambitious research and innovation outcomes.
5. Access to finance enabling the uptake of new technologies and the coverage of the related initial costs of adoption should be facilitated.
6. Global M&A strategies impacting European players should be foreseen as not to loose its best pieces to competitors much too early.
7. Monitoring acquisitions in the field as to be able to follow where the most important IPR portfolios are and monitor new market dynamics but also support and optimise collaboration models between science and industry (SIRE). Public entities should boost meaningful IPRs by bundling resources for top European research.
8. A position should be taken by public entities on how to encourage innovative behaviour in the construction sector and on how to discourage harmful conservative mentalities.
9. Current national and European regulation and policies are to be streamlined in order to clarify the extent to which regulation will be adapted as to scale-up living lab experiments into real commercial products.

4.2.10 3D-printed confectionery

CONTEXT. One of the grand challenges the global food market is facing is the growing demand for food that requires developing sustainable methods for food production, which in turn require increase in the efficiency of food production and processing. Consumer trends (willing to eat healthier food, etc.) are key in that respect as they drive the value chain. To meet the challenges, at least a partial switch to alternative food sources is expected by many. The food industry is relatively conservative sector in which most of the development is incremental, for instance in food processing it is aimed at the small improvement of existing technologies or at the replacement of minor steps in the food production chain to increase efficiency. But 3D-printed food should not be confused with industrial automation. Hence, 3D technologies have been applied also to food industry to print food, for instance to produce fun shapes but potential for the technology is also seen in more serious food products for consumers with special nutritional and dietary needs. The 3D food printer technology is still very nascent, the first patent application was published in 2007 and the patent landscape is dominated by Chinese (Frost & Sullivan 2015). The expectations for 3D printing in food are enormous although not realised in full, yet. 3D printing allows also flexibility to use alternative food ingredients which the industry will face in future to create improved products with respect to nutritional content, health benefits and shelf-life. The artisanal field of confectionery that produces decorative bakery products, chocolates and other type of sweets is one of the food industry fields which can benefit of the dimensions that the 3D printing can offer.

[285] A lack of focus from entrepreneurs on issues such as culture and design, IT and gaming, infrastructure, safety thinking (related to housing issues), standardization, sustainability.

SCOPE. 3D-food printing[286] offers solutions[287] for automation of cooking (e.g. 3D food vending machines), production of food in challenging spaces like in flights for sterility and taste, nutritional options for people with dietary needs, and also for designer food for its aesthetic value. Major challenges still to solve relate to the need for multi-material printing systems and integration with traditional cooking processes, like baking or boiling. One of the major hindrances is the low printing speed. But the food application area also entitled "3D-printed confectionery" (see Figure 25) was selected because of its potential for the food industry and because of European demonstrations and first commercial applications available already. The market entrance was therefore just achieved and adoptions can be observed (though deployment is far from being achieved). Confectionery appeared to be the most relevant area, in which the aesthetics and design are driving the adaptation of 3D printing rather than possibilities for personalised diet, for instance. At this point of time mainly research organisations are driving this change, although some industrial cases could be spotted – mainly in the context of collaborative projects. Research is being conducted on the consistency of food materials not to stick into the printing machine and to retain their form after printing. Another area consists in "how" to mix materials to create tasty products. Research in the field is also very much associated to developments in the field of robotics and food processing technologies as automation is sought by industrial players.

Figure 25: Illustrative applications of 3D-printed dessert decoration.

Source: Mei Lin[288]

Because of the negative associations related to confectionery products, product innovation and development is vital in this market. Due to the current health and wellness trend in food consumption, the revenue of the European confectionery product market is expected to decrease by 0.3% from 2013 to 2018 (Tosin 2014). In view of the negative associations in confectionery, like tooth decay, obesity and diabetes, there is also increasing governmental intervention, for instance placing regulatory standards. Because of their proximity, not only did the case study touch upon confectionery but also to another promising area which is the one of personalised food for consumers of special dietary needs[289]. Both areas are subject to similar trends and are at an early development stage. One general trend in food sector is the fragmentation that might create new business opportunities around 3D food printing. The benefits of AM in the food sector can be seen for instance in high material use efficiency and in production flexibility that allows fast responses to market requirements that both target to minimise food waste in food processing. Food AM is currently mainly a matter of fundamental and applied research. RTOs are therefore the current key players in this area. However, food manufacturers are eagerly following these developments. It has been estimated that various affordable food printers will be on the market in five years. In the late 2015, the most interesting and innovative solutions were developed by start-up companies, both Europe and the US, and the first of these 'kickstarter' projects are expected to materialise in one to two years. 3D printing in food is in explorative research phase. The key actors in the 3D-printed food are public and private R&D actors, who are testing and experimenting in collaboration mainly with small food companies, restaurants and chefs as well as some larger food manufacturers like Barilla.

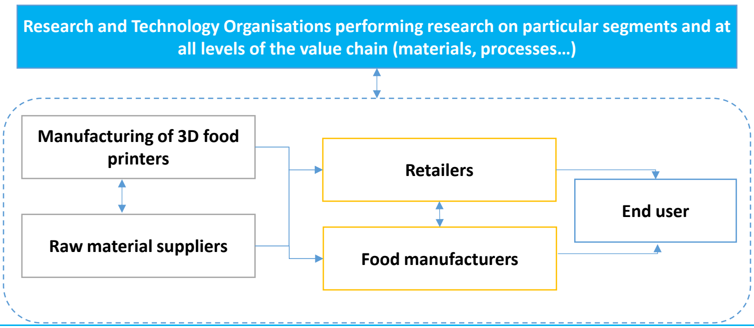
[286] 3D-printed chocolates and other decorations should not be confused with moulding which has already been developed for long in confectionery sector.

[287] The main technologies used in the food 3D printing are FDM (Fused Deposition Modelling).

[288] Mei Lin, winner of Bravo's Top Chef worked with 3D Systems Culinary to 3D print the passion fruit flavored cloche that tops her colorful dessert. [Photo courtesy of 3D Systems]

[289] Such as for elderly or people suffering from illnesses, athletes, etc.

Figure 26: Main segments of the confectionery additive manufacturing value chain



VALUE CHAIN. 3D food printing value chains are largely non-existent at the moment but some regional hotspots can be detected that shows initial clustering of 3D food printing actors. Although some of the confectionery producers are taking the first initial steps in 3D printing, chocolate printers are available on the market[290], like the Choc Creator by Choc Edge from United Kingdom, and American The Hershey Company's CocoJet which is developed in collaboration with leading American printer manufacturer 3D Systems Inc. 3D System's own ChefJet™ Pro is also used for printing confectionery. Pioneering consumer service concepts were also found. A UK-based confectionery maker, Katjes Fassin Ltd., commercialised the world's first 3D food printer for consumer retail, and opened in August 2015 a concept store in Berlin, called The Magic Candy Factory. One of the emerging regional areas in the 3D printing is Barcelona, in Catalonia, where activities are concentrated around the printer developer Natural Machines' Foodini and smaller players going through dinner experiments such as the restaurants Dos Cielos and La Boscana. Another identifiable regional ecosystem is in the Netherlands, which is strong in research due to strong RTOs (TNO in Eindhoven and Wageningen University in Gerderland) who collaborate with food manufacturers such as Marfo in Lelystad in Flevoland or smaller explorative startups and private R&D actors in customised confectionery. De Grood Innovations (NL) is one of the leading 3D printer developers in food. The multitude of different types of actors and capabilities in the Netherlands, makes the country a potential place to spot emerging value chains. In the UK some initiatives are based on university research which are however scattered. Printer developers spinning off from universities can be found near the University of Exeter (Choc Edge) and the University of Cambridge (nūfood printer). In the Bremen area (Germany), activities are centralised around Biozoon GmbH. In Germany, the activities are not concentrated in any region but are rather spread over southern Germany (Freising) to northern Berlin, where the first 3D printing candy store is located. The potential service providers in the 3D-printed food value chain are for instance restaurants, cafes and specialised shops (like Magic Candy Factory in Berlin), and grocery shops in which one could offer 3D printing services. At the moment, 3D-printed food products (and printers) are mainly offered via web stores. The consumers can be reached via thee main ways, serving them 3D-printed products in restaurants and cafes, offering them service to print personalised products (incl. on-line shops), or self-printing at home. The 3D food printers are expected to make their way to private kitchens alongside coffee makers.

Box 22: Missing and/or under-developed capabilities in this value chain include...

- Because of the scattered and small number of actors, one of the main missing capability in the 3D-printed food in Europe is the lack of specialization;
- The food industry is not only waiting good results from pilot production examples, but the machines and raw materials for industrial use are missing as well;
- The main activities in the 3D-printing in food are concentrated on few Western European countries, and no clear indication of companies or research actors from Eastern Europe that have engaged in 3D-printed food is available.

Capabilities are missing in Europe (see Box 22). Because of the scattered and small number of actors, one of the main missing capability in the 3D-printed food in Europe is the lack of specialization. There are not yet specialized areas with accumulated knowledge on specific application areas in the 3D food printing. The main reason is that Europe does not at the moment have volume in the 3D food printing area. Europe lacks actors in all areas, from research to retails, which prevents fully operating clusters and ecosystems to develop. Specialized regional competences are to arise only when there is enough critical mass. Current challenge to Europe is to increase the collaboration of scattered actors, and to share technologies and know-how. Current challenge to Europe is to increase the collaboration of scattered actors, and to share technologies and know-how. Fostering collaboration at European level is important in two aspects: including private unprejudiced innovative food technology companies into research projects, and improving knowledge exchange of European research organisations in common projects. Open knowledge sharing in an application area which is in the exploratory phase is fairly restricted. In addition, the food industry is not only waiting good results from pilot examples, but the machines and raw materials for industrial use are missing as well. Although many suitable food materials exists for 3D printing, not all food and ingredients are suited since material needs to have certain viscosity. For example, the biggest challenge for Choc Edge in developing the 3D technology was to find the right type of chocolate that would layer itself up (Frost & Sullivan 2014). Development and new innovations in these areas are important for manufacturers to adapt 3D printing in food production. Among them are the uses of

290 It could be said that consumer market for 3D-printed confectionery exists already as consumers are interested in personalised products, but from the industrial engineering and management perspective the exploitation of 3D food printing is not yet feasible.

new materials, including the process of bioprinting which resembles to the use of biomaterials for printing artificial organs (for transplants) and would target meat printing. Capabilities for developing feasible business models in 3D-printed food are to be strengthened as well. This would require further emphasis from the industry but also especially from research, like marketing and other business sciences. Adopting 3D printing in consumer markets, like food, paves the way for service innovation.

Finally, it can be seen that the main activities in the 3D printing in food are concentrated on few Western European countries, and no clear indication of companies or research actors from Eastern Europe that have engaged in 3D-printed food is available. Among the emerging trends is the one of using AM for more than only decoration purposes as well as to use it to design products that have a certain texture that cannot be attained using conventional production methods. Another emerging area is the one of dietary and nutritional food which has been subject to several experiments. 3D-printed food using alternative ingredients and materials to create healthy and tasty food is particularly growing. In the area of meals tailored to the nutritional needs of individuals, the Nestlé Institute of Health Sciences (NIHS) has launched late 2013 a project on how to meet dietary needs with 3D food printing[291]. Although the experiments in the dietary food sector are at very initial stage, the size of worldwide market is appealing to food manufacturing companies. To get some perspective of the potential market size, a closest market to this is the medical foods, which is not be confused with dietary supplements, drugs or food with a health claim. Medical foods are instead a special category of disease-specific foods administered to sick patients. Within the medical food market, the US and Europe account for the major share in market revenue (both more than 25 % each) and the global market is estimated to be $13.34 billion in 2018. Given that the medical foods are used for preventive care, a one of the major focus areas of health care in Europe, non-prescription medical foods account for a high share in market revenues (Balasubramanian 2014).
It should be noted that medical foods is a highly regulated area, which do not exactly comply with 3D-printed dietary and nutritional food discussed in this report. More futuristic experiments concern the use of bioprinting of living cells.

BARRIERS AND POLICY IMPLICATIONS. Heat and ingredient issues are limiting the performance and possibilities offered by AM in the food sector today. They are however not the only obstacles to AM. Food production takes place in various different contexts, and different venues such as restaurants and grocery stores may one day host 3D printers. Key barriers were however identified along this research. First, there is little accumulated research knowledge in this area. Only a few RTOs and universities in Europe have invested in research in 3D-printed food. Advancements are needed in several areas such as temperature fluctuations during the extrusion process. From the standing point of end-users, present organic & healthy eating trends prevent users to adopt 3D-printed food. Health-conscious consumers avoid additives which are often required for the proper structure of printable food mass. In addition, consumers are reluctant to pay the cost of 3D-printed food which is high and unaffordable for many consumers. In the same way food safety, especially regarding synthetic food, is a great concern for many end-users. That is in line with current regulatory preoccupations: currently there are no regulations in place that would deal with 3D-printed food; this prevents food manufacturers to engage in 3D printing in large scale. The lack of regulation affects food safety (incl. the hygiene of food printers) and the acceptance and image of 3D-printed food. The main challenges for not observing the value chains in commercial use are the lack of viable business models. The area is indeed not mature yet (which partly explains why IPR are not a key barrier in this area). The large European food producers, like pasta maker Barilla and Marfo from the Netherlands, are exploring the opportunities but the current 3D printing speed does not offer companies production scalability. Finally, not all food ingredients are applicable to 3D printing yet. This is closely related to the need for developing technologies to extrude multiple ingredients. These concerns set the basis for policy implications:

1. Awareness raising is needed to improve the image of AM in the sector. Communication should be addressed to all value chain actors, targeting specifically the industry and consumers to improve knowledge of the 3D printing in food sector, including technologies and potential business models. Promoting R&D by setting up targeted research calls and incentives to the stagnated food industry would encourage companies to innovate more.
2. European Fab Labs (Digital Fabrication Laboratories) should be used as test beds for food printing. Setting up shared facilities and platforms of 3D food printing at the current exploratory phase should be encouraged at the regional level.
3. Skills should be made available and AM should be included in food curricula (food sciences, processing technologies, business sciences, etc.). The development of business models should firmly be included in the European research agenda of 3D printing, and integrated to technological development.
4. Product safety should be addressed and included in a broader approach to AM. In food sector product safety relates to serving and distributing food, and issues such as labelling and marking of 3D-printed food. Futhermore, design rights should be followed when producing 3D-printed food, whether manufactured or designed by a consumer on the spot.
5. Collaborative R&D should be supported (through calls) but also coordinated at the European level. Designing research calls that include both innovative private companies and public research actors is important.

[291] Molitch-Hou, M. (2014) Nestle Wants to Meet Dietary Needs with 3D Food Printing, 24 June 2014. Available: http://3dprintingindustry.com/2014/06/24/nestle-wants-meet-dietary-needs-3d-food-printing/ (accessed 15.12.2015)

5/ Conclusion

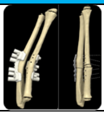
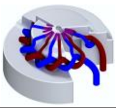
5.1 Regional AM supply capabilities in the EU: overview of a fragmented landscape

It is clear from the quantitative analyses that Europe is facing **strong competition** from global players and mainly from the United States and Japan. Europe still holds a strong position in terms of patenting: some AM service providers but also large multinational firms (incumbents from thematic sectors) perform well in European specialization areas such as aeronautics as well as electronics. Healthcare, energy and materials also fall under the scope. These players are mainly located in Western Europe, such as confirmed by the cross-validation operated with the analysis of FP-funded projects but also ny the application-driven case studies. It is possible to observe **leading European countries** such as Germany, the UK, the Netherlands, France, Belgium, Italy, Spain and Sweden take a global lead in some specific areas. The case studies show however that the **regional repartition** of current AM capabilities vary from an application area to another, mainly due to the differences observed in regional specialization profiles. Among the **key players**, German RTOs and Printer Manufacturers occupy a central position. This is particularly the case in the field of metal AM which is seen as a main strength of the European economy. They are followed by large RTOs and well-performing service providers who plug in to different value chains as to develop thematic capabilities. Large multinational firms active in digital solutions, new materials, electronic devices, etc. are also part of the technology developers as they seek to develop internal capabilities that will allow them innovate and derive value from a differentiating technology. Aerospace and healthcare seem to be on the forefront of public support at the European level. However, publicly supported Research and Development also addresses areas such as sector-related AM applications (in the automotive field for instance) or the use of materials such as ceramics or biomaterials in AM processes. Cross-cutting issues are also being investigating such as the combination of additive and subtractive forms of manufacturing. From a technical point of view, most research seems to be directed towards Selective Laser Melting and biomedical applications. The bibliometric analysis shows for instance that the most outstanding topics being researched in Europe relate to "*Biomedical Implants with Electron Beam Melting and Selective Laser Melting*", "*Mandibular Reconstruction Surgical Planning*" and "*Selective Laser Melting*". Subsequent analyses show that key players – among which leading printer manufacturers and large multinational companies – are indeed active in Europe on these segments.

The application-driven case studies show that the AM landscape is still getting off the ground and shaping up around key application areas. It is driven by factors such as materials or technologies used, management cultures, and these can vary from an application area to another. The role of certification is only one example in that regard. **Missing and under-developed capabilities** were identified for each of the value chains under the scope (see Table 12) as to complement the overview of the regional repartition of AM activities across the European value chains under study. They come together with the finding that capabilities should better be connected throughout Europe. Although AM players (companies providing services, systems, and materials for AM) are very often active in different areas, the landscape of AM capabilities in the industry remains **fragmented** with varying levels of use (when comparing small mold making companies compared to large integrators). It is particularly fragmented in areas where links are directly established between AM players and end-users (customers) such as in food printing or in the decoration field, where consumer participation is of main importance to the value chain. Some **concentration effects** can however be observed. The AM software segment, for instance, is clearly dominated by a few strong players from Flanders, Ile-de-France and some other Western regions (together with some non EU players also active in the EU). A similar pattern can be observed regarding AM powders.

Western European Countries are clearly on the forefront of AM developments. Large German Landers (Bavaria, Baden-Wurttemberg but also North Rhine-Westphalia) are beyond any doubt the regional systems where most AM capabilities are concentrated (and above all AM systems). EOS, Concept Laser, SLM Solutions, Trumpf, VoxelJet and ExOne are leading companies in that regard. They cooperate with leading RTOS and companies from Germany (LZN and the Universities of Fraunhofer, Aachen, Düsseldorf, etc.) and the Netherlands (TNO). They are followed by French regions such as Ile-de-France and Rhône-Alpes (where PEP, Fives, Gorgé, Phenix, etc. are active) and the United Kingdom where key players such as Renishaw and LPW lead the market. Italy is also developing capabilities, mainly in Northern Regions (Piemonte, Lombardy, Emilia-Romagna) where large industrial players are willing to investigate AM in the fields of automotive, aerospace but also packaging. Northern Europe (Sweden but also Finland and to a more limited extent Norway) are also strongly developing in specific AM areas (in Sweden, the machine tool and automotive industries are current [and potential] customers of AM products and services). Key players could also be identified in the Netherlands (South Netherlands for instance), Belgium (Flanders), Austria (Upper Austria for instance), and Spain (Asturias for example). **Eastern (and to some extent Southern) Europe** is however at a discovery stage. Although Poland is more advanced, countries such as Slovenia, Croatia, Slovakia, and the Czech Republic are only starting to develop capabilities in the research sector. Investments are being made by manufacturers of printers to enter Eastern European market but the state of play remains at a very early stage. Also service providers are important in terms of enabling traditional sectors: from that point of view, Belgium (with Materialise, Layerwise, and Melotte in Flanders) is among the Western European countries that draw on a strong knowledge basis. New players such as in the field of food AM are also developing in Cataluña on a less common technological segment (the one of meal printing).

Table 12: An overview of missing and under-developed capabilities per value chain under study

Application Area	Under-developped and missing capabilities
	**Surgical planning:** Materials capabilities (not only hard materials but also soft tissues, etc.); Capabilities are mainly concentrated in Western European regions; The software segment should further be developed.
	**Plastic-based car interior components:** The CAD software segment could be strengthened further; Capabilities are mainly (if not exclusively) concentrated in Western European regions.
	**Metallic structural parts for airplane:** Transformative capabilities to turn high-end materials such as titanium and alluminum into powders are missing in Europe; CAD capabilities should be further developed; Non-Destructive Testing (NDT) and broader testing capabilities; Post-processing (including finishing) capabilities should be further strengthened; Capabilities are concentrated in Western European regions; Wire-based AM systems and appropriate software capabilities are currently missing in Europe; Hot Isostatic Pressing (HIP).
	**Inert and hard implants:** Capabilities are mainly concentrated in Western European regions; Software (incl. simulation/modeling) capabilities should be further strengthened in the sense of customisation.
	**Metal AM for injection Molding:** Transformative capabilities in high-end powders; AM Supply capabilities are mainly concentrated in Western European regions and the users are part of a scattered landscape; Software capabilities could be further strengthened to face international competition.
	**Spare parts for machines:** All the value chain is currently at an early stage of development: no clear supply chain could be identified beyond specific (and/or isolated) cases; However, finishing and post-processing capabilities remain to be developed (surface finition is key to this application area).
	**Lighting and other home decoration products:** Although they are to develop, no particular capability appeared to be missing in this value chain – existing capabilities however remain to be bundled.
	**3D-printed textiles:** Software and simulation capabilities can be further developed; Adapted systems (in view of in-line production), incl. relevant interfaces; The landscape remains scattered; New (elastomeric, rigid, conductive, etc.) materials.
	**Affordable houses:** Overall the 3DP activities related to affordable housing are scattered over Europe with only few countries and some of their regions that do well such as the Netherlands and the UK. To reach critical mass it would be beneficial to bundle forces. Eastern-Europe seems not to have activities in this field apart from some SMEs activities from Slovenia. A majority of the most important activities seem to be concentrated in Western Europe (German speaking regions for material development and robotics, UK and the Netherlands). One additional missing capability is not technological but relates to the financing and ownership strategies of promising ventures especially in the fields of design and software development. It seems that the continuity of European ownership is not always realized in this field what may potentially hamper optimal growth of the company targets and their European ecosystems. Furthermore even and especially in countries that are active in the field there seems to be a need for 'bridging people' that understand robotics, software and the construction sector as to make development projects more successful.
	**3D-printed confectionery:** Because of the scattered and small number of actors, one of the main missing capability in the 3D-printed food in Europe is the lack of specialization; The food industry is not only waiting good results from pilot production examples, but the machines and raw materials for industrial use are missing as well; The main activities in the 3D-printing in food are concentrated on few Western European countries, and no clear indication of companies or research actors from Eastern Europe that have engaged in 3D-printed food is available.

While **large players** (mainly from concentrated sectors such as automotive) are steering some of the developments in the AM field, **SMEs** remain in a difficult position due to their limited capacities. The injection molding case was quite illustrative of the difficulties faced by SMEs when coming to explore AM, due to high technology access costs. **Research and Technology Organisations** (RTOs – such as CENTIMFE, CETIM, PEP, TNO, Fraunhofer, Produtech, Prodintech, SIRRIS and others) prove to be key in bridging AM and SMEs in that sense. There is still, however, a lack of visibility of available AM capacities in these technology organisations, both between the RTOs and the SMEs and between the RTOs themselves. Mapping these capabilities and improving access for SMEs still needs to be stimulated. Moreover, the integration of AM in many sectors clearly leads to technical advances and the birth of new business models as observed in the areas of surgical tools, in the automotive domain with LocalMotors (in which Airbus recently invested) or spare parts with Schunk[292]. An interesting area in that respect is "lighting and home decoration products", which is strongly oriented towards open source models[293]. The use of AM remains focused on well-defined areas, with parts and products that are mainly existing already but that can be improved and optimized (from both a technical and economic point of view). When considering AM, the usual "*nodes*" linking different value chains are printer manufacturers and services providers providing their inputs to two (Arcam AB) or more (EOS) sectors. Connections across value chains can be observed for instance in sectors involving heavy machinery such as automotive and aerospace sectors. This is also the case in injection molding and spare parts for machines, since both areas are by definition linked to multiple value chains. The development of AM remains slow in many areas. For example, the AM of textiles is clearly an area developing very gradually: upcoming applications beyond the manufacturing of shoe soles or protective textiles are rather the expection and other applications are only anecdotic due to current technical limitations (e.g. textile printing).

Competition is mainly coming from the US (to some extent also IL) as AM (3D-Systems and Stratasys in the first place) but also industrial leaders (Ford, Boeing, etc.) are dominating the markets under the scope world-wide. American players are implementing particularly aggressive acquisition strategies and acquired a number of main European players recently. Europe still shows particular strengths, for instance related to the **metallic AM** cluster spread over the German landers of Bavaria, Baden-Wurttemberg and North Rhine-Westphalia[294]. Also Asian companies (mainly from Japan and China) such as DMG MORI or MAZAK are very active in Europe and gradually propose competitive products such as new hybrid printers. It is important to take into account the strength of the European players in various fields of metal Additive Manufacturing. US-based companies (including Stratasys which is also located in Israel) have a clear lead in most plasti-based application fields while Asian players are either competitive on a specific line of systems (like Japanese companies in the field of Hybrid Manufacturing) or in emerging areas (like Chinese companies active in bioprinting).

5.2 From fragmentation to collaboration

Taking into account the fragmentation of the European AM landscape, one can note that the concentration in particular Western European regions (Flanders in Belgium, Baden-Wurtemberg in Germany, etc.) relates to a form of **specialization** in specific supply or demand areas underlying the AM value chains analysed in this study. Whether these value chains are subject to missing or under-developed capabilities or not, the absence of balance between Western and Eastern European regions remains clear. It can however be taken as a **collaboration opportunity**. During the research, a number of collaboration opportunities were identified in that sense:

- Collaborations that take or could take place **across value chains**, very often on the basis of similar technical concerns (the use of particular systems and/or materials, the manufacturing of particular parts of products, etc.);
- Collaborations that take or could take place **along each value chain**, very often on the basis of strengthened collaborations between the various segments of the value chains under the scope and/or the communities and organisations at stake.

In both cases, collaborations can take place between specific actors acting in a same (regional) **ecosystem** as one can observe in the field of AM for injection molding; or across European value chain segments (whether across or along value chains) such as observed in the case of the collaborative projects and platforms linking the automotive and aerospace AM value chains. **The levels of AM regional specialisation and related fragmentation in Europe particularly call for international and cross-regional collaboration**. Such collaborations (each being value chain-specific) can or could link Western and European regions, supply and demand in an open innovation fashion. With some concrete examples, Table 13 lists the key collaboration opportunities identified during the case study research for each of the application-driven value chains under the scope.

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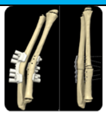
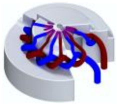
292 Schunk is a German company that has set up an online platform to sell gripper fingers in collaboration with Materialise; See also http://www.schunk.com/schunk/schunk_websites/news/subject_of_the_month.html?article_id=25113&country=INT&lngCode=EN&lngCode2=EN .

293 The example of 3dhubs referred to in this case is illustrative in that respect.

294 While European players are leaders in the field of metal AM, the United States drive the main developments in the area of plastic AM. Food and housing-related concrete for AM remain specific niches.

Table 13: Overview of the main collaboration opportunities identified for the 10 application-driven value chains

Application Area	Collaboration opportunities
	**Surgical Planning:** Multidisciplinary collaboration is needed. Communication, collaboration, exchange of experiences between the different actors (material providers, service providers and users - surgeons and hospitals) is key. The same goes for universities and businesses. Especially at the level of materials, the very detailed and focused approach of material research is indicated as useful for the companies to further develop applications in healthcare.
	**Plastic-based car interior components:** Collaboration platforms already exist between the automotive and aerospace sectors; as for the other collaboration opportunities in the sector, these are by nature European (and international/global). They are mainly to take place between OEMs, AM service and printer providers, RTOs and integrators. Collaboration opportunities also exist between the car interior component value chain and other transport-related value chains in Europe. These could be concretized by dedicated collaborative projects/platforms/networks (EU scale); Other collaboration opportunities could be spotted such as between the car interior value chain and the textile value chain (through upholstery). International collaboration could take place between research centers and OEMs on this topic. Collaborations with other value chains could also take place on the basis of either the materials or systems mobilised by the sector (plastics, composites, powder bed systems).
	**Metallic structural parts for airplane:** Collaborations could take place across value chains on the topic of large metallic structural parts, and mainly between the aeronautic, automotive, defense and space value chains. Such collaborations could be organized at the EU level and link key OEMs and integrators but also 3DP service and printer providers active in those value chains across regions and along the value chain. Collaboration opportunities are also found in the areas of smaller structural (and non-critical) components across the aforementioned value chains, these could take place at the EU level and involve similar players. Platforms, networks, projects and other collaborative settings would be appropriate to foster such collaboration as is already being done under H2020; Collaborations across regions could take place in this area but also making the link between this value chain and other value chains (such as in the transportation and Energy fields where common constraints apply) by connecting demonstration and testing facilities across regions. This could be done bottom-up with the coordination support from the EU level. Collaborations could finally take place around titanium-based applications which are in use in the aforementioned value chains (common AM parts were already identified that can be found in both aeronautics and space systems).
	**Inert and hard implants:** Multidisciplinary collaboration is needed. Communication, collaboration, exchange of experiences between the different actors (material providers, service providers and users - surgeons and hospitals) is key. The same goes for universities and businesses. Especially at the level of materials, the very detailed and focused approach of material research is indicated as useful for the companies to further develop applications.
	**Metal AM for injection molding:** Collaboration opportunities exist between OEMs, integrators and mold-makers but also research centers in all value chains making use of injection molding. Such opportunities can concretize at all levels (along the value chain and locally between mold makers and RTOs or AM expert companies, cross-regionally between mold makers and OEMs, etc.); Particular collaboration opportunities could be taken advantage of cross-regionally in the areas of car manufacturing and packaging (where AM molds could play an important leverage effect).
	**Spare parts for machines:** Collaboration opportunities are spotted between the machinery (incl. Equipment manufacturing) and mass production sectors (automotive, packaging, etc.); Collaborations have to be developed around the combination of subtractive and additive technologies, most likely in a cross-regional fashion, and should involve both science and industry.
	**Lighting and other home decoration products:** Regarding the relatively high involvement of European users (see e.g. Fab Labs or 3D Hubs) within 3D-printing platforms, specific opportunities for Europe could be supported financially and with specific actions, e.g. establishing initiatives such as Fab Labs, especially in Eastern European countries. Potential key regions with high concentrations of involved end users and vendors of 3D-printed home decoration products were identified (e.g. Netherlands/Nordrhein-Westfalen, in Italy, South France, and in Spain). Networking activities, knowledge exchange platforms, and other actions could support local players and raise common awareness.
	**3D-printed textiles:** Especially collaborations between research institutes and textile industry (including between designers and OEMs), and also with 3D-printing end users, including 3D-printing communities. Opportunities emerge in suing textiles in other industries such as automotive and aircrafts (Cross-sectoral collaboration). Collaborations should be supported, especially between research institutes and textile industry. Collaborations with companies from Eastern Europe where many textile manufacturers are located (although they are often subsidiaries from MNE).

	**Affordable houses:** Collaboration between various value chains e.g. construction sector with aerospace industry and defense industry both on national and European level. More collaboration is needed between different fields. Especially cooperation between architects and experts from robotics, software and construction industries is needed.
	**3D-printed confectionery:** Fostering of research collaboration at European level by including private unprejudiced innovative food technology companies into projects, and improving knowledge exchange of European research organisations in common projects. Sharing of facilities and platforms of 3D food printing at the current exploratory phase should be encouraged at the regional level. Encourage research partners to adapt open innovation and co-creation principles. This would also potentially lead to the development of stronger regional ecosystems linking research organisations and the food industry. The research of 3D printing in food would benefit of European level research projects that integrate technology and business development. Understanding from food processing technologies, business models and consumer acceptance are to be strengthened simultaneously.

5.3 Aiming toward the disruption of European AM value chains: emerging and future areas

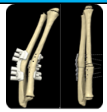
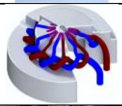
The study of the structure and mechanisms of the 10 AM-driven value chains is a reminder that most application areas are still at an **early stage** of development. The areas under the scope are indeed concerned with different levels of maturity. One could position the selected areas as follows:

- **Mature AM areas** are the pioneering areas (TRL 8-9). These include the surgical tools (and in particular surgical planning tools), hard and inert implants, injection molds with conformal cooling as well as aircraft structural components. These entered or are entering the market as they could benefit from the comparative advantages of AM regarding short series production (mainly product optimization and customization). However areas such as healthcare and aerospace face strict regulations which drives airplane manufacturing companies for instance to focus their use of AM on non-critical components such as interior components.
- **Intermediary areas** include all components in the car manufacturing industry (both car interior and demanding components) (TRL 6-8): although AM is not used for production in this sector, it is extensively used for prototyping and tooling. Also in the food sector, the use of AM for confectionery is at an early stage but shows an existing market and consumers.
- **Less mature areas and emerging areas** include textiles 3D printing (with printing of soles for shoes is the most advanced area) and the printing of spare parts for machines (TRL 5-7). Also construction AM is part of this area as it recently moved to full-scale AM of houses and has a commercialization horizon of 5 to 10 years. Home decoration AM is still a niche and can therefore fall under this category.

The established value chains under the scope are therefore **not disrupted yet** by the integration of AM technologies. However, some **changes are taking place** that can be summarized as the **contraction of some value chain segments at the product level**. This is the case when AM is used for specific products and leads to 'shortening' the supply chain. AM printer manufacturers and service providers, for instance, are somehow *"by-passing"* some of the traditional players (steps) involved in the initial value chain: AM is for instance competing with injection molding in many sectors where protototypes can be printed and do not require molds anymore, or in sectors where it doesn't pay off to have expensive injection matrices given the production size (e.g. in aerospace for the production of polymeric cabin components in aircrafts). In the case of surgical tools, AM service providers directly provide surgeons and hospitals with AM tools. One can also observe an increase of the involvement of 3D-scanning companies in this value chain, increasing the importance of scanning companies in the value chains underlying inert implants for instance. Collaborations are being put in place as service providers collaborate for instance with heavily regulated sectors such as in healthcare and aerospace. Thus for some particular products only, AM is disrupting the existing value chain(s) but did not completely impact the position of traditional players in their respective value chains; or it leads to the setting up of new forms of collaboration between newcomers (AM players) and traditional players.

A number of key **emerging areas** (see Table 14) such as in the field of personalized food or smart textiles, for instance, remain highly promising and could prove to be disruptive. Table 14 provides an overview on all emerging and future areas spotted during the case study research and at the level of each of the application-driven value chains under the scope. These are at different stages of advancement and are subject to various levels of expectations. In the fashion textile area for instance, the role of designers holds a particular importance but raises questions such as IPR. Other emerging trends such as in the decoration product and spare parts markets suggest that completely different chains could emerge if digitized platforms allow for collaborative and localized production. Such assumption(s) should however be carefully assessed as both areas are at a niche stage. In the spare parts or in the machinery segments, AM has been largely exploited for fast-prototyping, but not yet taken up more broadly by industrial players. New applications are expected to grow such as in the field of bioprinting (closely related to the printing of implants) or food (where AM is still an early-stage niche market that is slowly developing). Emerging areas also relate to upcoming developments seeking to overcome the limitations of current technologies. AM is a technology that indeed faces many **limitations** (high cost, slow production rate, limited surface quality, etc.). It however proved to be relevant to many needs and demands from many industries regarding the possible integration of parts, new designs and optimized parts and products. Moreover, the social benefits that could be derived from AM at the end of the value chain are also of main importance: whether it concerns more precise tools for surgeons or lighter airplanes with reduced CO2 emissions, AM clearly has the potential to contribute to address Grand Challenges. Although their level of maturity varies, all present cases show **promising economic potential**. Both emerging and future trends were identified in the case studies such as regarding the development of multi-material printing, hybrid manufacturing, food bioprinting, etc.

Table 14: Emerging and future AM areas - An overview derived from the application-driven case studies

Application Area	Emerging and future AM areas per value chain
	**Surgical Planning:** Soft and flexible materials. Currently surgical planning is still mainly focused on hard tissue in the body. A large part of the body consists of soft tissue though. The materials for e.g. cardiovascular and gastrointestinal models requires elastic properties from the material. There is still a lot of potential in modelling and simulation for surgery. Very important is the identification of the problem and the quantification of the problem (diagnostic purposes). 3D-print enabled surgical planning services (induced by the availability of AM models and surgical tools/guides and the need for software and specialist service providers.
	**Plastic-based car interior components:** Printing of lightweight and/or complex parts; Composite materials for car interior component printing; Hybrid printing methods; Customized 3D-Printed cars and related business models (such as in the case of LocalMotors); Decentralised and on-site production of parts (at dealership, etc.); Printing of large components; Full production scale printing of car components; Full car printing; Multi-material and multi-color printing; Integration of components through AM.
	**Metallic structural parts for airplane:** 3D-Printing of large components and structures (aircraft wings and fuselage are current targets); Wire-based printing of metallic structural parts, which is currently at a demonstration stage; In the longer run, some see the printing of entire airplane structures as a possible (though still speculative) future area; Maintenance, Repair and Overhaul (MRO) and on-site production of (spare) parts for aircrafts; AM of small critical components and mechanically loaded parts; Use of composite materials in the printing of structural components; Development of proper monitoring and control mechanisms.
	**Inert and hard implants:** Bio-degradable material (in the next 5 years); 3D-printing of drug (in the next 5 years); Bio-printing (20 years or more).
	**Metal AM for injection molding:** AM for thermo-plastics injection molding; AM for injection molding in specific mass production sectors such as automotive (thermal exchangers, light components, and new solutions for gearbox) and packaging (bottle caps, etc.); Hybrid systems to 3D-print injection molds; Pre-series production; Prototype molds printing; Full development of digital solutions; Multi-material molds.
	**Spare parts for machines:** Maintenance, repair and overhaul (MRO); Distributed manufacturing and on-site printing of spare parts for machines (business model evolution); Non-strucural machine parts - which are not subject to guarantee issues; Spare parts for machines used in mass production sectors (automotive, packaging, etc.); On-demand (platform-based or through hubs) printing of spare parts for machines; Design selling (instead of parts).
	**Lighting and other home decoration products:** 4D printing, which will be delivering definable and varying material qualities, including electronic qualities, within one printed object, will open potential application fields for consumer products, especially for lighting products; Specific and various material qualities will be possible within one printed object, including electric conductivity.
	**3D-printed textiles:** New technologies and combination of printing materials, as well as input from other printing techniques, such as ink-jet printing, help to develop new applications thus leading to new and fast developments of 3D-printing technologies; Leight weight constructions; Smart Textiles (Electronics).
	**Affordable houses:** Printing entire buildings requires new AM solutions. One key solution offered is the use of very large printers that do either produce large pieces that can be assembled into bigger structures or come up with entire units such as rooms or houses. Another alternative and more flexible solution - the combination of robotics and AM technology - comes into play when the pieces are bigger than the printers; Online applications will appear where clients can customize their houses. New business model could appear where people can order new doors or new colors for their house even by paying monthly fees or membership money (e.g. Spotify); Temporary buildings like pavilions for festivals that only stand for a few days/weeks - or shelter in disaster areas.
	**3D-printed confectionery:** Personalised food (like adding proteins, vitamins etc) for special nutritional and dietary needs (e.g. people suffering from illnesses, elderly, health consious consumers); Substitute and alternative food materials (e.g. using insects as source of protein, 'meat' like vegan products); Emerging service innovations (e.g. new ways of serving food that create socio-technical change).

5.4 Toward a faster uptake and deployment of AM in Europe: policy implications to address the barriers to AM uptake and deployment

Key barriers were identified along the research process for each and every one of the application areas referred to under Section 4/. Barriers were observed which related to a broad number of policy areas. The lack of knowledge is among the most recurrent ones and mainly consists in the lack of skills and appropriate curricula, but also in the lack of knowledge available to characterize and standardize the AM materials and processes at stake. Key Research and Development tracks were identified in that respect as highlighted in Box 23.

Box 23: Research and Development tracks

- **Examples – AM Materials**: Biodegradable materials, Composite materials, Material feedstock, Materials explosivity, Materials toxicity, Metal material properties, Multi-material printing, Recycled materials, Cellulose fibres, Health impacts of AM powders.
- **Examples – AM Processes**: Diagnostics and sensoring, Digital Design / CAD, Hybrid manufacturing, Large parts printing, AM Processes, AM efficiency, Quality monitoring and control, Software development.

The technical limitations but also the cost of printers and a persistent lack of awareness among potential user communities are also recurrent barriers. They come together with difficulties to overcome traditional ways of manufacturing and cultural barriers in private organisations. Barriers to the uptake and deployment of AM along the selected value chains are also strongly linked to the structure of the market and composition of the chain (including underlying mechanisms such as the bargaining power or demand). It is also important to highlight that some of the barriers that appear to be critical relate to missing knowledge or capabilities. Two main missing segments where no or few European players are active are in that respect:

- High-end metal-based material capabilities, and in particular transformative capabilities of materials such as titanium, aluminum and magnesium (see Box 24);
- And the post-processing segment (where Hot Isostatic Pressing is absent and finishing as a whole is to be developed).

Box 24: Eye On the Issue of Metal Powders – The focus on transformative capabilities

It has been acknowledged that AM materials require further development[295]. The present report mainly highlighted the critical importance of **aluminum**, **titanium** and to some extent **magnesium** to the European AM industry. Among the three types of materials, only magnesium (which is also used in almost all aluminum alloys) was considered a critical material in 2010 and in 2014 as 96% of the supply came from the 20 most significant producing countries and 86% from China[296]. While there is in addition "*no significant production [of] (…) titanium in within the EU*"[297,298, 299], Europe is an aluminum producer[300] and a leader in aluminum recycling[301]. The titanium industry is concentrated in both supply and demand markets, pursuing its vertical integration. Aluminum on the other hand is subject to a low level of concentration. Metals such as aluminum and titanium in particular are concerned with both **technical** and **economic difficulties**, and **processing** appears to be a main challenge[302]: skills, knowledge and modeling are areas that require further support in that respect. One can notice that AM is not among the largest consumers of metal powders. These are however **critical to the AM industry**. The present report shows that besides raw material supply, **transformative capabilities are the ones to be further developed in Europe**. These consist in activities aiming to (and related organisations able to) transform and recycle (raw) materials into proper AM materials (such as powders, wires, etc.). This segment was found as being a key missing/under-developed capability.

Table 15 provides a summary of key barriers per application area listed from the application-driven case studies.

[295] Measurement Science Roadmap for Metal-Based additive manufacturing. National Institute Standards and Technology, US Department of Commerce. 2013. http://www.nist.gov/el/isd/upload/NISTAdd_Mfg_Report_FINAL-2.pdf

[296] Source: http://www.polinares.eu/docs/d2-1/polinares_wp2_chapter2.pdf

[297] Source: http://ec.europa.eu/DocsRoom/documents/10010/attachments/1/translations/en/renditions/native

[298] In Europe, only Norway produces titanium (See http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical/index_en.htm).

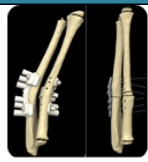
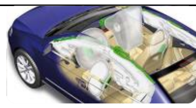
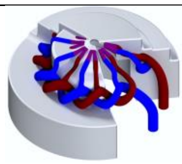
[299] See http://titanium.scholarlab.com/customer/titanium/resources/tieurope2014/SchneiderUweWorldIndustryDemandTrendsTiEU2014.pdf

[300] https://ec.europa.eu/growth/tools-databases/eip-raw-materials/sites/rawmaterials/files/Bauxite%20-alumina%20-aluminium%20Presentation%20.pdf

[301] See http://ec.europa.eu/growth/tools-databases/newsroom/cf/itemdetail.cfm?item_type=251&lang=en&item_id=7054

[302] Source: https://ec.europa.eu/research/industrial_technologies/pdf/metallurgy-made-in-and-for-europe_en.pdf. Pg.46.

Table 15: Overview of the main barriers hampering AM uptake and deployment in 10 application-driven value chains

Case Study	
Surgical Planning: lack of training and appropriate skills (CAD, management, manufacturing, etc.); the lack of a multi-disciplinary approach; the lack of awareness across the user community; the fact that printers remain expensive and not precise enough; the rise of virtual reality technologies allowing for virtual planning and therefore competing with AM-based surgical planning.	
Plastic-based car interior components: limited performance of AM regarding efficiency, surface quality, automation, scale economies and the printing of large parts; the fact that 3D-printed parts remain expensive and not fully sustainable but also that post-processing is still needed; the lack of qualification of AM materials and processes as well as appropriate design rules; the lack of appropriate curricula and skilled workforce; the risk-aversion and manufacuting conservatism of company and technology managers; design/CAD IPR.	
Metallic structural parts for airplane: rising competition from composite materials; heavy regulations; lengthy development plans; the lack of knowledge and skills; printer manufacturers' strategies regarding powder uses (use of specific powders made conditional to the use of certain printersà; the need for common standards and further characterization of AM materials and processes; missing knowledge (about health and security implications of AM); scalability issues; poor quality and surface finishing; the lack of detection, monitoring and control of surfaces; the lack of transformation capabilities in Europe and the availability of high-class, passivated clean powders, including aluminum, magnesium and titanium; the lack of streamlined information and insufficient awareness.	
Inert and hard implants: this area is constrained by users' low adoption level; certification requirements and related uncertainties; IPR and regulation concerns; technical isssues; the quality and availability of relevant materials; the current regulatory framework; limited skills and technology development (including R&D/characterisation and standards).	
Metal AM for injection molding: printers and powders remain expensive (mainly for SMEs) but also faces issues such as: skills availability; growing demand toward AM system manufacturers; cultural conservatism; lack of AM awareness; lack of demonstration activities; lack of multi-disciplinary curricula; AM technical limitations (cleaning of cooling channels, printing of large molds, precision and surface finishing, etc.); insufficient qualification and certification of AM materials and processes; transformative capabilities in the field of metal powders; players standing as bottlenecks in the field of metal powders[303]; fear of having companies' designs stolen; development of internal AM capabilities in client companies; little bargaining power of SMEs; international competition coming from plastics and composite materials; design/CAD IPR.	
Spare parts for machines: AM is expensive and sub-optimal; appropriate skills and curricula; risk-avoiding culture; availability of spares; need for a clear available distributed network; designs availability; printers' warranty and replicability of the parts; missing knowledge about AM materials and processes;; differences between materials, printing conditions; lack of precision of AM.	
Lighting and other home decoration products: technical limitations (production time, finishing, quality, toxicity, stress testing, costs); need to develop materials and processes (incl. 4D-Printing); the market is small and dedicated to expensive designer products; only few key players are active in this area; missing knowledge about 3D-printing; consumption is low; awareness and quality information are missing.	
3D-printed textiles: lack of technological knowledge; missing fast in-line processes; insufficient mechanical properties; inadapted textile CAD data; insufficient resolution; need for process and materials characterisation; need for simulation and software; AM productivity; lack of common research and interactions between key players; concentration of supply capabilities in Western Europe; limited performance (size of the product, printing length, costs; missing material (from elastomeric materials to rigid or conductive materials) and finishing capabilities; lack of new business models; strength and quality of materials.	
Affordable houses: limitations of current robotics and printers; no part integration, multiperformative and multimode operations; need for computerized assembly lines; size, volume and cost of AM; complexity of human/robot interactions; materials; scale; speed; skills; current paradigms; conservative and risk-avoiding culture; lack of multi-disciplinarity; lack of awareness; standardization, building and safety regulations; lack of creative entrepreneurship[304].	

[303] e.g a printer manufacturer conditioning the use of its printers to the use of its powders.

[304] A lack of focus from entrepreneurs on issues such as culture and design, IT and gaming, infrastructure, safety thinking (related to housing issues), standardization, sustainability.

3D-printed confectionery: Heat and ingredients; AM performance; missing knowledge; lack of critical mass; knowledge about temperatures during the extrusion process; consumption habits; image of AM food; price of AM food; food safety; absence of regulations; lack of viable business models; not all food ingredients are applicable to 3D printing yet; need for technologies to extrude multiple ingredients.	

Policy implications were derived for each of the cases which are presented in details in Section 4 of the Background Report. An overview of key policy implications is provided in Annex 3. These imply that an EU strategy for AM is to be reflected on in the first place. When conducting the cross-case analysis of these policy implications, the following headings and indications were identified that synthesize the key fields for which public action is needed:

Acting at the level of Human Resources

1. **Skills** and the availability of appropriate and **multi-disciplinary[305] curricula** are a crucial issue to be addressed. This was identified as a key barrier to be overcome in all case studies. Training should be made available which would deal with AM and particular aspects of AM (such as CAD, materials, management, etc.). Such development is most likely to take place at the level of EU Member States, but the European Union could take a coordination role in order to streamline efforts made in this area.
   - *A consultative process could for instance be launched by the European Commission which would trigger collaborations between education stakeholders and the AM community. This participatory process could gather relevant stakeholders and key organisations to shape up a new ground for multi-disciplinary curricula at all education levels and how to ensure their uptake.*
2. **Awareness** should be raised at all downstream levels of the value chains under the scope: engineers, technicians, R&D and company managers, but also consumers and end-users in general should be made aware of the pros and cons of AM in order to allow for the necessary cultural shift. The so-called cultural shift both concerns the focus on formative and subtractive methods as well as the reluctance to adopt new – less proved – technologies.
   - *Two main tools could be mobilized in that respect: first, the European Commission could initate a one-stop shop that could take the form of a website dedicated to Additive Manufacturing and of which content could deal with the various aspects of AM in Europe but also world-wide (incl. links to calls for projects, an interactive mapping of key AM infrastructures and services, etc.). A second tool would be thematic events to target 1) (potential) users and 2) company managers. These events would be oriented toward particular issues that are key to the competitiveness of particular value chains or application areas.*

Acting at the level of the technology

3. **R&D support** (including experiments and prototyping) is required in all areas, whether emerging or already advanced. Technical barriers related to the size of the printed parts, the efficiency of the process, etc. are key barriers to be overcome in order to make sure AM reach an appropriate level of maturity in the areas where Europe has or can develop a comparative advantage. R&D support is most likely to be collaborative in order to allow for knowledge and technological transfers and broader diffusion. By collaborative, it is meant that R&D should bring together RTOs, large companies and SMEs, as well as users[306]. Such support could be brought at the regional, national and European government levels.

Box 25: Examples of R&D areas to be supported

- **Surgical Planning**
  - Research on materials: (a) on elastomeric type of materials which can be used for medical models and (b) multimaterial printing;
  - Research on the accuracy and the fidelity of the 3D-printed models;
  - Design features for 3D-printing[307].
- **Plastic-based car interior components**
  - Quality, consistency of production outputs;
  - Composite materials for car interior component printing;
  - Application of biomimicry to the AM of car components.
- **Metallic structural parts for airplane**
  - Explosivity of metallic nano-sized powders;
  - Quality of material feedstocks in powder-bed AM systems;

[305] When taking the example of affordable housing, such multi-disciplinarity could involve mixing robotics, software and construction, with particular emphasis on design and software development. In the food sector, these would entail food sciences, processing technologies, etc.

[306] And to the extent relevant government authorities.

[307] Currently the design process of 3D-printed implants is very long and complex. There is certainly a need for further improvement of the medical imagine-processing software. The "connection" between CT-data and intelligent design of applications can still be improved.

- Properties of large multi-material and composite-printed structural parts for airplanes.

- **Inert and hard implants**
  - Research on materials: the strenght and porosity of the inert and hard implants (towards the future: futher research on biodegradeble materials and bio-printing);
  - Design features for 3D-printing[308];
  - Userfriendliness of the user features of 3D-printers. Often there is no automation or only semi-automation.
- **Metal AM for injection molding**
  - Bi-material (copper and steel) mold printing;
  - Hybrid printing and the finishing of cooling channels in injection molding;
  - Inter-operability of metal powders such as titanium and aluminum powders.
- **Spare parts for machines**
  - Post-processing and the finishing of surfaces with mechanical properties;
  - Hybrid manufacturing (combining additive and subtractive techniques) of (non-) structural components for machines such as air compressors, compellers, water pumps, separators and parts of forging machines;
  - Analysis of distribution patterns of spare parts for the development of additive/subtractive hubs.
- **Lighting and other home decoration products**
  - AM processes; Printing qualities are still not sufficient for small objects and products often need further surface treatments after printing;
  - Material properties; Technological advancements, e.g. 4D printing, which will be delivering definable and varying material qualities, including electronic qualities, within one printed object, will open potential application fields for consumer products, especially for lighting products;
  - Toxicity, explosivity and broader health impacts of used materials.
- **3D-printed textiles**
  - Quality monitoring, control and detection systems;
  - Recycling and sustainability are the strongest arguments for 3D-printing as production can be achieved without too many remnants and waste;
  - Materials selection, materials properties including health impacts (esp. also recycled materials, such as cellulose fibres).
- **Affordable houses**
  - Materials should still be developed that can be processed on printers or contour crafting machines and that can fit the requirement of the building industry;
  - How AM, robotics and automation together can change the way things are done in the construction sector[309];
  - Software development.
- **3D-printed confectionery**
  - Technologies of 3D food printers (e.g. temperature fluctuations during extrusion process, printing speed);
  - Creating of multi-textural food structures (e.g. printing of different layers with materials that have different viscosinity);
  - Research in viscosity and consistency of food materials (e.g. particle size of printanble materials).

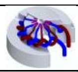
– R&D support would most likely be collaborative and applied cross-regionally. A broad range of instruments could be mobilized in that respect: networks of infrastructures connected across European regions and coordinated at the regional level; collaborative R&D projects supported by regional, national and European authorities; as well as other targeted tools such as innovation vouchers or financial incentives (R&D tax credits at the national level, etc.).

4. Among the key areas to be supported, the **combination (and comparison) of subtractive and additive methods** (for instance in the form of hybrid manufacturing) is to be supported in order to make Europe able to compete with Japanese competitors on a high-potential segment.
5. Europe is well-placed to **streamline all standardization and certification efforts** being made in the context of different value chains. The inter-operability of materials is for instance a key area where public support would benefit the industry. It is however important to note that standardization is only useful when the technology is characterized and mature enough. Examples of possible working areas relevant to standardization efforts are provided in Box 25, showing that qualification is to remain a priority in some of the application areas under the scope.

[308] Currently the design process of 3D-printed implants is very long and complex. There is certainly a need for further improvement of the medical imagine-processing software. The "connection" between CT-data and intelligent design of applications can still be improved

[309] The assumption is that the industry is not only going to use 3D-printing but a whole set of different operations into the building process. In the factory of the future, they see the building process completely robotized. Alternatively robotics could be included in the 3DP category or appear as another value chain with which collaboration has started

Box 26: Working areas to guide standardisation - Examples

Area	Description of the working area	Status
	Standards on classifying and labelling 3D printed food are needed. 3D printed food safety regulation, mainly in serving and distributing food (e.g. hygiene of self serviced 3D printers and vending machines at supermarket, producing food vs selling packaged food) is also a key area.	*Standardisaton working areas*
	Standards should be found in the field of plastics used as material for car interior components and which should present certain mechanical properties.	
	Powders inter-operability in order to ensure the operational functioning of powders in powder-based systems.	
	Metallic powders should be subject to further characterisation before being subject to standardisation. Standards should be developped for powder-based systems but are also needed for wire-based processes to spread.	*Characterisation and standardization running in parallel for different systems*
	Several materials used for 3DP are currently being investigated and their properties are actually not known yet, meaning that standardisation can only happen at a later stage. Qualification will therefore matter in that respect.	*Qualification and certification as main priorities*
	Regulatory framework: uncertainty with respect to certification at national and EU-level hampers the uptake of AM. A clear regulation with respect to certification should be developed.	

6. European **Fab Labs** (Digital Fabrication Laboratories) should be **used as test beds[310]**. Regions would be well-placed to steer such tests due to territorial proximity.
17. Another example of policy implication relates to **Intellectual Property Rights (IPR)**. The current analyses suggest that **monitoring** and **enforcement** could reduce the risk-avoiding behaviour of most companies active in different markets and who could take advantage of AM depending on the area (see Box 5). Examples of actions are listed below, which are illustrative only (further analysis is recommended to assess the need and usefulness of the listed examples):
    - Information capabilities of key Intellectual Property instances could for example be strengthened by setting up an observatory (which could be related to the EPO and/or IPO for instance)[311] in order to watch over new industrial designs and their reproduction.
    - IPR regimes could be enforced at both EU and national levels. This particularly concerns the protection of design patents and copyrights over original parts.
    - Monitoring acquisitions in the field of construction AM would allow following where the most important IPR portfolios are and monitor new market dynamics.
    - Meaningful IPR could be boosted by bundling resources for top European research.
    - In the field of consumer products, IPR helpdesks and IPR support from the public could also cover new forms of IPR such as creative commons, rules concerning open source software development, etc.
    - In sectors such as mold-making and textiles, activities supporting the involvement of users could have an open source character. Collaborative contracts with RTOs should in any case be made clear and SMEs could be supported, protected, and informed about the possible options available to protect their designs.
    - Collaborations could be foreseen in order to capitalise on upcoming working groups and current progress in the definition of AM-related IPR lines[312].

[310] This is applicable to all value chains, with a particular interest from the side of food printing and textiles.
[311] Examples are provided in http://www.tandfonline.com/doi/abs/10.5437/08956308X5705256 and on http://ubiquity.acm.org/article.cfm?id=1008537
[312] See for instance https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/421543/A_Legal_and_Empirical_Study_into_the_Intellectual_Property_Implications_of_3D_Printing_-_Exec_Summary_-_Web.pdf as well as https://www.gov.uk/government/publications/3d-printing-research-reports.

Box 27: The importance of IPR - Addressing current and anticipating on future issues

Although IPR were identified as current barriers to the adoption of AM[313] in the mold-making and automotive sectors, they are not perceived as main barriers to the deployment of AM in the aerospace, surgical planning and spare parts cases[314]. In the first two cases, the key IPR issues relate to AM designs and copyrights. Industry players fear that their designs could be stolen and that their parts/tools could be reproduced. In addition to those two groups, 3D-printed hard and inert implants, confectionery, affordable houses, home decoration products and textiles are areas where IPR issues could arise in the future but such development is to be approached carefully. Policy implications were therefore suggested in line with the different levels of maturity and related importance of IPR issues.

Developing missing or under-developed AM capabilities

7. As already pointed in the case studies, the access to high-end materials is crucial. Europe is subject to missing capabilities in this area. Therefore, European and National but also regional entities should facilitate the **access to critical materials[315]** (titanium, aluminum, magnesium, etc.) and more precisely develop the related **transformative capabilities** by supporting initiatives such as:
   - Market intelligence;
   - Improvement of business development conditions;
   - Capacity development through co-investment (in transformative processes for instance) that could take the form of direct R&D support or financial incentives;
   - Support to the qualification and standardisation of the materials through strengthened coordination at the European level;
   - Urban mining[316] to be developed at the local level with the support of higher levels of government.
8. Other capabilities should be further strengthened, for instance using similar tools than the ones referred to in the context of supporting metal powders transformative capabilities:
   - Some functional capabilities are still missing in Europe that are crucial to the further deployment of AM. These mainly concern **finishing** and in particular **Hot Isostatic Pressing** in the field of metal AM.
   - Other capabilities should be developed or reinforced at the level of the first segments of the AM value chain. These include 1) **simulation** and 2) **testing**.
9. The development of **new business models** should be supported: new business models are indeed required in areas such as food printing but also in automotive where companies such as LocalMotors in the US already introduced a new form of car manufacturing to the market. This is also the case for the textile value chains where user-driven **platform-based models** are to be further explored.
   - Digital policy should therefore foster intelligence in the field and facilitate the testing of new business models (at both European and national levels).

Bringing AM applications closer to the market

10. Closer to the market, **pilot production and demonstration capabilities** remain to be supported and connected across European regions. **Cross-regional demonstration activities** should be supported as well as **joint actions** and collaborations among exising actors, whether on a case-by-case basis or through (a) one-stop-shop(s). This would allow a better connection between supply and demand as well as to flow knowledge and network towards Eastern European regions.
    - The European Commission could take an orchestration role in that respect, by supporting the setting up of relevant networks, structures and upgrading of current/emerging capabilities.
    - First of all, the lack of visibility and the absence of clear overview of AM capacities in RTOs calls for a **mapping** of such capabilities (including equipment and infrastructure but also services).
    - **Specific technologies** could be targeted: wire-based technologies are close to market deployment for instance and hybrid systems are reaching a demonstration phase. These are examples that should be further supported and are further detailed in the case studies.
    - During the case studies it was confirmed that **cross-regional collaboration** would be appropriate to address the fragmentation of AM capabilities in Europe.
11. **Collaboration is to be fostered** (see examples in Figure 27).

[313] IPR are a key issue in all value chains under the scope. They were however not identified as key current barriers to the adoption and/or deployment of AM. In most value chains, the weight of IPR as a policy issue is expected to grow, but it is recommended not to design and implement policy in a premature fashion.

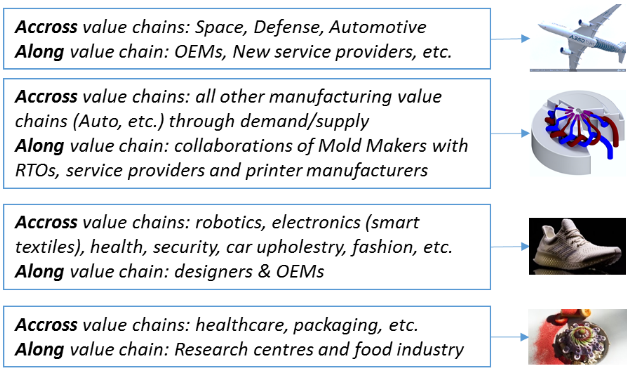
[314] In the field of spare parts AM, the issue rather relates to the general terms and conditions that are contract-based and lead to conditions over the warranty associated to one or another machine.

[315] Through certain initiatives such as studies and projects, the EC contributes to this ambition. One can for instance refer to the study on the legal framework for permitting, Horizon 2020 project MIN-GUIDE developing a European Guide to Minerals Policy, Horizon 2020 project MINATURA2020 developing a concept of Mineral Deposit of Public Importance to secure access to deposits. A part of Horizon 2020 will also most likely contribute to put in place appropriate framework conditions, social aspects and industry competitiveness, as well as appropriate policy settings. Among others, the EC collaborates with the European Institute for Innovation and Technology (KIC on Raw Materials) on setting up a European Investment Platform on Raw Materials and Recycling in the framework of the European Fund for Strategic Investments.

[316] 'The process of reclaiming compounds and elements from products, buildings and waste.

- Collaborations could be triggered on the basis of similar technical concerns (the use of particular systems and/or materials, the manufacturing of particular parts of products, etc.) shared by key actors from different value chain segments.
- While **existing** collaborations (between automotive and aeronautic players for instance) can be supported, the **emergence** of others also requires public intervention (such as in the case of injection molding where collaboration between RTOs and mold-makers is to be facilitated). A wa to trigger such collaborations would be collaborative R&D support but also cluster initiatives that could be supported by national and regional entities in collaboration with the European Commission.
    i. **Cross-value chain fertilisation** would allow speeding up the market deployment of AM across value chains. There is a clear opportunity for European authorities to take advantage of existing (nascent) collaborations and foster the emergence of new collaborations across value chains[317] on common AM issues.
    ii. Not only collaboration can take place across value chains, but also **along relevant value chains** by fostering collaborations between segments such as presented in Table 34 which provides selected examples of possible collaboration opportunities both across and along value chains.

Figure 27: Collaboration opportunities along and across value chains – Selected examples



Stimulate and orient the demand side

12. Whether emanating from users or consumers, demand is key to most AM value chains under the scope. There is an **opportunity to stimulate demand** in an appropriate way across the value chains under the scope.
    - This could for instance go through integrators in the automotive market, the consumers in the food market, etc. Affecting food preferences or using regulation could impact the growth of AM deployment in many value chains.
13. Demand could be activated in different ways depending on whether the demand is rather baded on Business-to-Business (B2B) or Business-to-Consumer (B2C) mechanisms:
    - From a B2B perspective, two possibilities arise:
        v. The price of AM is a recurring issue that keeps SMEs with limited capabilities but also larger risk-avoiding **companies** from investing in 3D-Printers or AM services. **Co-investment** is therefore needed from public authorities in order to facilitate the **testing** and the **acquisition** of printers. Innovation vouchers could for instance be used to facilitate the access of SMEs to relevant Research and Technology Organisations (RTOs). Tax (credit) schemes or other financial incentives could also be mobilized in that respect.
        vi. Another aspect is based on the findings from the aeronautic value chain under the scope. It is showed in this case study that environmental regulation can affect airlines, which put pressure on integrators and OEMs so that they design and manufacture optimized airplanes with reduced levels of CO2 emission. Similar mechanisms could be applied to a broad range of application areas as to foster the deployment of AM.
    - From a B2C perspective, **user platforms should also be financially supported**, especially in the benefit of Eastern European regions so **that** Fab Labs can emerge across Europe. Platforms and networks for consumer participation could for instance be strengthened in fields where consumers play a key role such as in wearables, homen decoration but also confectionery.
14. In all fields a need for a **common repository**, **streamlined information and awareness raising** was **flagged**. This could be operated at the European level in order to make sure that a homogenous set of information is managed and diffused, not to be confused with marketing by potential user communities who would be the main target.

[317] For instance between defense, automotive, space, aeronautics, transports; but also between textiles and a number of other value chains; etc.

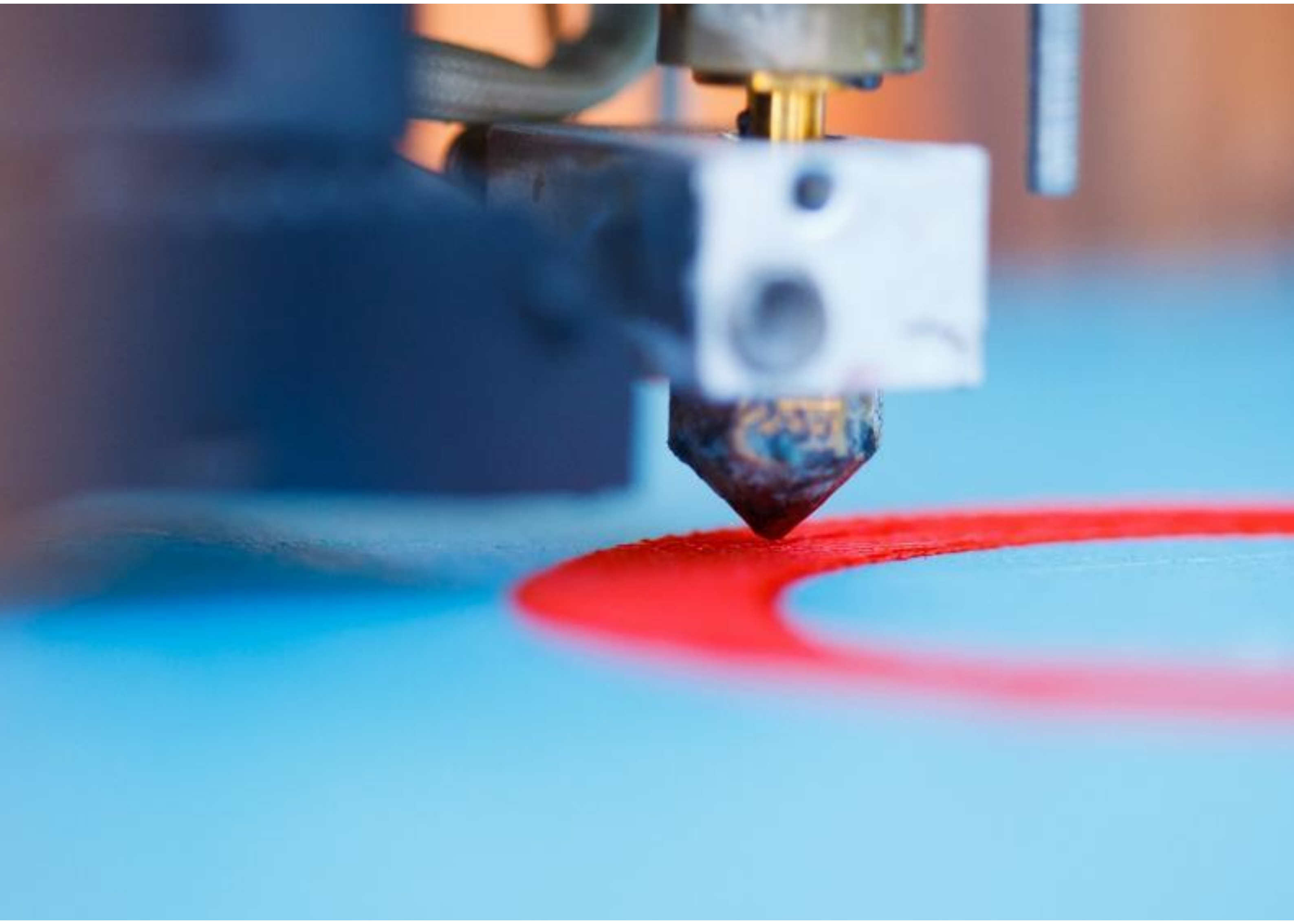
- An example could be to have a one-stop website (serving as repository of information) sponsored by the European Commission and managed in collaboration with research and industrial communities such as suggested under the first heading of policy implications (Point 2). Such website could among other things aim at clarifying the European AM landscape, make clear the pros and cons of AM, and stand as a gate for organisations willing to collaborate on specific AM developments.

15. Current national and European regulation and policies are to be streamlined in order to clarify the extent to which **regulation** will be adapted as to scale-up living lab experiments into real commercial products.

Box 28: From AM applications and value chain analyses to policy analysis

This study developed knowledge about European Additive Manufacturing value chains. It depicted to some extent key areas of action to support the adoption and deployment of Additive Manufacturing as well as the structuration of 3D-Printing value chains in Europe. Dedicated research would however be needed to assess the potential effectiveness of specific policy tools and instruments to address the key needs, barriers, challenges and opportunities identified in this report. Such study could develop an analytical framework to study the effects of specific policy instruments over the process of additive manufacturing deployment.

Background Report



1/ Introduction[318]

This **Background Report** provides the details of the qualitative and quantitative analyses leading to the results showcased in the core report. This background report combines all project outputs. Three interim reports were produced by the research consortium along project implementation in order to showcase the results of the different analyses.

The structure of this background report is organised as follows:

1. The first part of the background report is dedicated to a **review of the literature** based on the **desk research** performed by the team to identify key sectors, applications and actors involved in Additive Manufacturing in Europe today. This review led to the first inputs to the Sectors-Applications Matrix used to position sectors, applications, and key players of 3D-Printing in today's European economy. This matrix was the main information repository used to select value chains to be studied in depth by the research consortium.

2. The second part of the background report provides more details on the **quantitative analyses** and the matrix resulting from both these and the **desk research**. This section of the report describes in a sequential order:
    a. The patent data analysis;
    b. The analysis of FP-funded projects;
    c. The bibliometric analysis;
    d. The resulting Sectors-Applications Matrix.

   The results from these analyses led to additional inputs to the **Sectors-Applications Matrix**. They also provide an overview of key issues such as regarding the relative position of Europe in some scientific fields related to AM, or more broadly the technology trends going on in the area.

3. The third and last part of the report is consistuted of 10 in-depth **application-driven case studies**. These case studies are value chain analyses. Each of them takes the perspective of an application or homogeneous set of applications and depicts the underlying **Additive Manufacturing value chain**. These cover the following areas:
    (1) Surgical planning
    (2) Plastic-based car interior components
    (3) Metallic structural parts for airplane
    (4) Inert and hard implants
    (5) Metal AM for injection Molding
    (6) Spare parts for machines
    (7) Lighting and other home decoration products
    (8) 3D-printed textiles
    (9) Affordable houses
    (10) 3D-printed confectionery

These value chain analyses led to the identification of each segment of each value chain. This entailed the identification of key actors and their current position, but also an analysis of trends and critical factors shaping the uptake and deployment of Additive Manufacturing in each value chain. An analysis of the **barriers** and obstacles that hamper or even block the uptake and/or further deployment of additive manufacturing in each application area was performed and **policy implications** were identified.

Following the background report are the Annexes compiling relevant material and evidence from the above analyses. Among others, these annexes present an indicative list of key players involved or concerned with one or more of the above application-driven value chains.

[318] CREDIT: The picture of the cover page of the Background report is issued from http://blog.sproutwatches.com/index.php/2015/01/3d-printing-future-of-eco-friendly-fashion/

2/ Literature review

2.1 Approach

In this task, the team performed a comprehensive desk research on 3D-printing to identify the most important current and future sectors and applications that will be affected by 3D-printing. A literature survey of recent scientific articles, conference papers, various news sources and reports was carried out. The aim of the literature review was threefold:

1. To identify most relevant **sectors** which are -or will be- impacted by 3D-printing
2. To identify most relevant current and future 3DP-**applications**
3. To identify **actors** and regions

The desk research (including key literature) was carried out by domain experts and information specialists. It produced several hundred hits, which were then classified by order of relevance (from relevant to not relevant). There were roughly 150 relevant papers after the preliminary classification. These papers together with material found on internet were used as sources for identifying the sectors. The team also used several reports and analyses identified already at the preparation stage of this study. 3D-printing applications, sectors as well as other relevant information were then extracted to complete a first draft version of the SAM table. The draft version was then reviewed and after initial modifications, more detailed information was gathered.

A key criterion to select the most important and relevant applications and sectors was 'added value that Additive Manufacturing brings in', i.e. business drivers relevant for that application. However, while there are great advantages that 3D-printing can bring, there are still several limitations, which reduce the range of reasonable applications at the moment. Typically, these limitations are related to e.g. productivity, costs or quality. Thus, in the selection of application areas, the team focused on applications where the business drivers were strong enough to overcome the potential current drawbacks of the advanced manufacturing technology.
Another key criterion for the selection was the maturity of the area. The team focused mainly on applications, which were assumed to reach commercial stage approximately after 3-5 years. There are interesting applications currently under research but if commercialisation takes years, it is challenging to evaluate the potential of the application.

Third criterion for this selection was that there should be enough organisations (within the supply chain) working in the field so that dynamic progress in that field would be more likely to take place.

Results
In the following sub-sections the major findings of the review are summarised. This summary will help the reader in view of reading the sectors application matrix (SAM) in which the results of the review are presented in a systematised way.

2.2 Aerospace

The Aerospace sector has been one of the early adopters of 3D-printing. Currently, according to the Wohlers report 2015, this industrial sector covers 14.8% of the revenues of 3D-printing industry (i.e. machines, materials and services). The aerospace industry includes design, manufacturing and operation of aircrafts and spacecrafts. The main drivers to use 3D-printed parts in aircrafts are reducing the weight of the components without sacrificing their performance, and reducing the buy-to-fly ratio. According to Sunday Times of 13th Feb 2011, the aviation industry has calculated that they could save 350 billion dollars in fuel costs within the next 30 years, just by using lighter parts manufactured by digital manufacturing technologies. By utilizing topological optimisation and other digital modelling tools, new materials and digital manufacturing, parts can be designed to be much lighter but still present equal or even better performance. In addition, part consolidation i.e. printing parts in a single piece instead of several fitted together, reduces assembly costs. Parts are used in rather small quantities, and they have often complex geometries as well as advanced materials, which might be challenging to manufacture by conventional means.

On the other hand, the aviation industry is very strictly regulated. Approvals of new components or materials take a long time. Early 2015, GE Aviation announced the first approved 3D-printed part certified by the US Federal Aviation Administration (FAA) for a commercial jet engine. The fist-sized T25 housing for a compressor inlet temperature sensor was fabricated by GE Aviation and will be retrofitted to over 400 GE90-94B jet engines on Boeing 777 aircrafts. According to GE, making T25 would have taken far longer using conventional methods. Other benefits include designs that were previously impossible, faster turnaround times from design to finished product, as well as much lower manufacturing costs with very little waste. If the benefits of using 3D-printing are big enough, it can be used also for volume production. GE expects that it will produce fuel nozzles in quantities exceeding 40,000 per year. In 2012, GE acquired Morris Technologies, US biggest Additive Manufacturing service provider, to produce aircraft parts.

The new Airbus A350 contains more than 1000 3D-printed flight parts, printed mainly by Fused Deposition Modelling (FDM) technology. These parts are mostly so called non-structural parts, i.e. not critical parts. The main driver to produce parts additively is the same: producing aircraft parts which weight 30 to 55 percent less, while reducing raw material used even by 90 percent. Military aircrafts have used 3D-printed parts even earlier than commercial aircrafts. One of the most well-known examples of production parts is air ducts for Boeing fighters. Boeing announces that it has produced more than 100,000 production parts by 3DP. Other components that have been additively manufactured include for instance electrical boxes and brackets. In January 2014, BAE Systems flew a Tornado with some of this aircraft's metallic parts made by a 3D-printer.

Spacecrafts are ideal targets for additively manufactured parts. They are produced in very low volumes, but they contain several, complex and demanding components. The European Space Association (ESA) is very actively seeking new possibilities to use these technologies. The NASA has successfully tested the most complex rocket engine parts ever designed by the agency and printed them thanks to Additive Manufacturing on a test stand at NASA's Marshall Space Flight Center. Actual flight-parts are currently on their way to Jupiter in the Juno spacecraft. Several parts for CubeSat satellite were produced additively by laser sintering. ESA has listed various potential parts to be produced by Additive Manufacturing: different structures, multifunction casing, RF filters, optical base plate, bracket and injectors as well as various on demand tools. Printing in space craft or space station could be also beneficial in future to create e.g. spare parts or tools. This has been already demonstrated by NASA where an astronaut printed a missing socket wrench in a space station. In August 2015 companies Made in Space and NanoRacks signed a deal to build & deploy 3D-printed satellites in orbit. Theoretically, 3D-printing will allow assembling spacecrafts in space or on the moon using locally available materials. The ESA is working on the concept of moon-based 3D-printing. The latest generation of printers has been used by the American defence consortium Lockheed to make parts of a telescope that will be sent into space around 2018.

3D-printing can be used, not just to produce new parts, but also to repair existing parts. Hybrid technologies combining conventional machining and especially directed energy deposition (DED)-type technologies are intensively studied, especially when related to aerospace and military sector.

From the material side, ceramics appear to be an interesting group of materials, especially for harsh environments like with very high temperatures. Ultra high temperature ceramics (UHTC) such as $ZrB2$ and ZrC can stand extremely high temperatures (>2000°C) and are cover a very high potential when thinking of applications like hypersonic flight systems and rocket propulsion systems.

2.3 Automotive

The Automotive industry has been the main pioneering industry in terms of using 3D-printing technologies. Large car manufacturers invested in 3D-printing machines soon after the first systems were commercialised (i.e. 1988). The utilisation of 3D-printing for rapid prototyping has increased the product development cycle remarkably, and prototyping still plays a very important role in the automotive industry. This industrial sector is usually understood as about the manufacture (including other supply chain steps) of passenger cars, trucks and busses as well as of light commercial vehicles, excluding special vehicles like tractors, cranes and other similar vehicles. Thus, typical production volumes in the automotive industry are too high to use Additive Manufacturing economically to produce final parts. However, increased requirement for personalised or customised products has increased the interest to use Additive Manufacturing also for final parts production. The demand for producing eco-efficient cars is another driver to design cars and components, which are light weighting and more energy efficient, thus suitable for 3D-printing. Another driver towards additively manufactured final parts is the competitive demand to produce new car models even faster than earlier.

In addition to visual models, which help engineers and designers to get a common understanding and communicate ideas and verify designs, prototyping models can be used also to test functionality of different parts, i.e. as functional prototypes. Recently, we have also witnessed various printed concept cars, visualizing new ideas in car design. These prototypes are used to test for instance the usability of parts and whole cars, but also to test the functionality of a specific part, like air resistance in car body parts, oil flow in power train systems or ergonomic testing.

Since the first automated production lines of Ford, the automotive industry has always been a frontrunner in using new technologies to increase productivity. In car manufacturing, there are various assembly steps, where 3D-printed assembly tools can increase productivity. In addition to assembly, there is need for jigs and tools also for instance in body shell construction and painting. With 3D-printing, complex shape jigs can be manufactured economically and tools and tool inserts without physical mould.

Racing cars are real life test benches for 3D-printed parts. Since racing cars are manufactured in low volumes and there are huge expectations for their performance, 3D-printing fits very well into the production of many car parts. There are various examples of different car components manufactured additively (e.g. CO filter housing, gauge pods, wheel arches etc.). Actually, a whole racing car (body), called Areion, has been 3D-printed by Group T together with Materialise using stereolithography technology. In addition to the car body, Additive Manufacturing is also used in Areion to optimise cooling channels as well as to print different nozzles and other parts related to cooling.

Recently, Local Motors announced a launch of a "3D-printed electric car" targeted for customer markets. Car body as well as chassis and some exterior and interior features are 3D-printed using ABS plastic reinforced with carbon fibre. The mechanical components like motors and battery are not printed but sourced elsewhere. This is a very interesting step towards using 3D-printing also in volume production. The car should be available in 2016. We can expect this trend of using Additive Manufacturing for final part production to continue and expand. Currently, the motor vehicles sector corresponds to 16.1% of Additive Manufacturing usage according to the Wohlers report 2015, thus being the third largest industrial sector benefitting from 3D-printing.
Light commercial vehicles are potential applications for 3D-printing. By definition light weighting is an important issue in these vehicles, and it could be approached by utilizing topologically optimised 3D-printed parts. In addition, typically these vehicles are produced on lower quantities and customisation and personalisation could also provide them with a remarkable role.

2.4 Healthcare

The healthcare industry is one of the world's largest industries with a fast growth rate. The Wohlers report 2015 estimates that medical and dental sectors corresponds to around 13.1% usage of Additive Manufacturing. In the healthcare sector, 3D-printing is currently used and especially in applications which require personalisation or mass customisation. On the other hand, like for the aviation industry, the medical sector is heavily regulated, which slows down the utilisation of new technologies and especially materials.

There are some well-known applications where 3D-printing is used successfully. For instance, there are more than 10 million hearing aids which have been produced by Additive Manufacturing. Actually, a majority of hearing aids manufactured in the US are produced with 3D-printing. The main driver to use 3D-printing has been simplified production chain, consisting nowadays in only three steps instead of nine. Hard implants, especially acetabular cups, have been successfully 3D-printed and implanted to patients. The capability to produce a both fully dense and porous structure for the same implant is a great advantage of 3D-printing. Porous surfaces are helpful for implants so that they will better be fixed to surroundings. Tens of thousands of 3DP-fabricated metal implants are produced every year.

In the dental area, Invisaling dental braces are probably the most well-known commercial dental products, which make use of 3D-printing. Braces are produced indirectly: thus, first the moulds are 3D-printed and then the braces are manufactured using these moulds. The main driver to use 3D-printing here is its capability for mass customisation. Several millions of moulds are printed every year. A similar approach is in use for producing dental crowns.

Surgical visualisation aids, so-called preoperative models (prototypes) are the earliest application areas in the medical industry. The planning of a demanding surgery is easier if there is a corresponding anatomic model available, derived from a patient scan. It can also be used to explain the operation to the patient. 3D-printed surgical tools could be used, especially in demanding and isolated operation environments (e.g. during various crises). Simple medical suppliers (e.g. stethoscope) are produced already today.

Prosthesis is also an application, where the capability of personalisation underlying 3DP is a clear benefit. Prostheses are placed externally to the body, thus they are non-invasive and should also be non-irritant. The use of 3D-printing can simplify the production process remarkably, therefore causing also cost savings. For instance, facial prostheses are already produced commercially by 3D-printing, and there are serious attempts to bring other prostheses to 3D-printing production as well. In addition, we have seen several Do-It-Yourself (DIY) arm prostheses, which could help in the future some people to live a better life in some developing countries.

3D-bioprinting or tissue engineering (also called organ printing) is a topic that is heavily researched globally. According to Murphy and Atala (2014), two-dimensional products (like skin) will be first applications, followed by hollow tubes (blood vessels etc.) then hollow organs and finally solid organs. However, there are still several challenges to overcome before this area can be subject to commercialisation. Printing itself is not the most challenging part. An approach in this sector is to use scaffolds, which might be 3D-printed. In addition to the healthcare industry, other industries like cosmetics and military are very interested in this application.

There are also other application areas under research, like 3D-printed drugs i.e. smart medicine and different kinds of medical micro-factories and lab-on-chip.

2.5 Machines & Tooling

This sector includes industrial and business machines as well as all kinds of tooling. According to Terry Wohlers the group "industrial and business machines" consists of office and industrial automation machines and equipment. Examples are document printers, computers, routers, CNC machines, robots, etc. This group is the leading industrial sector in Additive Manufacturing applications. According to Wohlers Report 2015 its share was 17.5 % in 2014.

The traditional way to exploit 3D-printing is prototyping in product development. A very interesting area in the future will be printing of spare parts on spot of demand. Examples of uses of 3D-printing to produce new types of innovative products are a low cost 3D-printed robot arm and innovative heat exchanges. Generally speaking, components with potential for customisation, lightweight, internal channels/structures, functional integration, design surface structures, or specific material options, are good candidates for 3D-printing.

Additive Manufacturing offers the possibility to manufacture tool steel moulds inserted with conformal cooling, and so to decrease the cycle time in injection moulding and die casting. Also the scrap rate may decrease and the quality increase through optimal cooling. New hybrid machines, combining machining and Additive Manufacturing, are excellent for making mould inserts. There are several manufactures of hybrid machines, like Matsuura in Japan, DMG Mori (Japan/Germany), Hermle (Germany), and Mazak (Japan). It is also possible to add Additive Manufacturing to existing CNC machines. Optomec in the USA and Hybrid Manufacturing Technologies in the UK are offering such options.

In injection moulding it is possible to use a 3D-printed mould insert from plastics for short series and prototyping. This shortens remarkably the product development time and reduces the costs. Other good examples for applying Additive Manufacturing in tooling are sheet metal tools, robot grippers, patterns for sand casting, and fixtures and jigs for welding and assembly.

Additive Manufacturing is also used e.g. for making patterns for investment casting and sand moulds for foundries when individual components or short series are needed.

2.6 Electronics and electronic devices

An interesting group of Additive Manufacturing for electronics industry are Direct Write technologies by which one can create two- or three-dimensional structures such as antennas and many kinds of electronic circuitry directly onto flat or conformal surfaces in complex shapes, without any tooling or masks. A good example is printing on mobile phone covers. The main companies in the area are from the USA based on a major programme by DARPA in the 1990s. One of the leading companies is Optomec with its Aerosol Jet system. In March 2013 Aerosol Jet system was used to print a conformal sensor, antenna and circuitry directly on a FDM-printed wing of a UAV (unmanned aerial vehicle) model. According to the Winter 2013 Newsletter of Optomec, it was the world´s first fully printed electromechanical structure.

An important step in applying 3D-printing to electronics is conductive filaments based on normal filament materials like the ones of ABS or PLA. Normally it is a question of blending carbon black etc. into base material resulting in e.g. 15 Ωcm resistivity at PLA and 10,000 at ABS. A much lower resistivity of 0.6 Ωcm, has been achieved by graphene filament based on PLA and developed by Graphene 3D Lab.

The conductivity of metal-based inks, especially those based on silver, is much better than carbon-based filaments. The newest development in the area is to co-print FDM filament and conductive ink and to produce so functional objects using only one printer. In American Voxel8´s printer plastic is extruded out of one portion of the print head and the conductive ink is dispensed out of another in order to create electric traces. The printer is pausing at the appropriate moment during print task for the manual embedding of components, such as transistors and resistors, within the print. Picking and placing functional objects will be automated later according to Voxel8.

Embedding stereolithography is a new approach for flexible manufacturing of mechatronic modules under research in Germany. The method combines stereolithography and UV-laser sintering of silver ink.

Thermal management is an ever-growing issue in the electronics industry due to the miniaturisation of devices. 3D-printing technologies open the way to new heat exchangers either using more complex and efficient shapes or more integrated complex frames including cooling channels manufactured in one single part. For microelectronics new 3D-printing methods like two photon polymerisation provide new potential.

Google's intended to use 3D-printing technologies for the manufacturing process of its new modular smartphone Project Ara. However, these thoughts have been placed on hold but the company is still involved in AM development.

2.7 Consumer life style & fashion (including textiles and creative industries)

Consumer life style and fashion sectors can be divided in two areas in relation to 3D-printing: (1) industrial products that have been made by using 3D-printing and (2) consumer 3D-printed products, which consumers have produced themselves by using inexpensive desktop 3D-printers. Typical products that consumers print themselves (e.g. toys, avatars, home decoration etc.) fall in this category. A hype related to consumer 3D-printing has brought a lot of public visibility to this sector. General drivers in this sector are related to the possibility to print series of one, typically.

The fashion sector (textiles, shoes, garments) uses 3D-printing to create eye-catching dresses and bikinis, for instance. Since these clothes are based on hard polymers, they might not yet be the most comfortable to wear, but surely gives new ideas to designers. There are attempts to develop methods to create fabric-like prints, however they are still under research and still need much more development to improve the comfort and flexibility of the textile for garments in order to produce truly wearable apparel for daily use. 3D-printing is currently used to accessorise garments. New materials (textiles) are developed, e.g. Dutch fashion designer Iris van Herpen who has developed new materials out of two totally different materials; one soft, the other hard that were printed together. This would mean that there are more possibilities in specifying on flexibility within printing a garment. 3D-printing allows adapting to customer demand quickly (e.g. fashion trends).

Jewelleries are also 3D-printed, and there it is possible also to use precious metals like gold and silver. Indirect methods (3D-printed mould and casting) are also used. Jewellery could be one of the industries in which 3D-printing will become a mainstream technology. 3D-printing is changing the economics of the jewellery design market drastically, independent designers (entrepreneurs) are now able to bring their designs into the world easier, breaking down the production process and opening the possibility to occupy specific positions along the value chain (e.g. design, 3D-printing services). The driver is creating complex structures which are difficult to produce by other means. Personalisation can be also considered as of importance.

Sport accessories and clothes is another important application area in this sector – as user of 3D-printing technologies. Nike has been a forerunner and used this technology in its products. The technology has been used to develop better cleats for football shoes, for instance. 3D-printing has been used also to create concept tennis rackets and similar products.

The consumer sector includes various applications, and new ones are clearly arising. Typical demands related to these products are e.g. ability to print in full colours, safety of materials etc.

2.8 Oil & Gas

The oil & gas industry is concerned with the exploration, extraction, refining, transportation of (usually by oil tankers and/or pipelines), marketing and distribution of petroleum products. Production takes often place in remote locations, which creates potential logistical problems related to e.g. spare and wear parts. Instead of transporting those parts to oil platforms, some of them could be printed on site. Oil and gas companies are moving also into the more extreme environments such as ultra-deep-water or arctic environments, which creates totally new requirements for the equipment. In addition, handling gas and oil effectively requires pumps, pipelines, valves, drills etc. which could be optimised (gas & liquid flow) by using optimisation tools and manufacturing them additively.

The way is being paved to move from prototypes to mass manufacturing of oilfield equipment on a large scale. However, the average size of equipment in this industry is commonly too big for 3D-printing at the moment. So a market is there for small and complicated parts as only these are cost effective with 3D-printing. However, the development of new, bigger equipment (typically based on directed energy deposition technology) could change this situation drastically. Another barrier is the harsh environments in which the operations take place. The quality and strength of the components has to be top notch.

Currently the use of 3D-printing in the oil & gas industry is quite modest and focused mainly on prototyping. However, there are some public examples of final parts manufactured additively. General Electric's oil and gas division has announced that they will start producing fuel nozzles for gas turbines additively. They will also invest $100 million on Additive Manufacturing technology development in this sector. Another potential application, according to GE, is electric submersible pump used to artificially bring oil to the surface. Oil service company Halliburton has produced parts additively for drilling.

3D-printing has also been used in production of smart pipeline inspection gauges (PIG). While pigs are custom-designed for particular pipeline, 3D-printed prototypes help in sizing of these gauges, and thus increase production speed of them.

The next big step for the oil and gas industry, beyond GE's 3D-printed nozzles, could be subsea pumps that help lift oil and gas out of wells. Sensors also could be an early use. One big opportunity may come from manufacturing customized equipment, where only a few products are needed -- instead of 100s coming off an assembly line. Mario Azar, the global head of Siemens' oil, gas and marine business, noted hurdles to use 3D-printing to outfit offshore oil and gas operations. "*You are dealing in harsh environments, so there's a threshold to how far you can go*", Azar said. "*You're looking at structures and equipment that need to last 20-plus years in a very, very harsh environment*".

2.9 Energy

According to Dr. Navrotsky from Siemens Power Service, the company uses Additive Manufacturing for rapid prototyping, rapid repair and rapid manufacturing. Rapid prototyping has reduced significantly time to market for e.g. new turbine blades. Burner tips of gas turbines can be repaired ten times faster than earlier. New types of burner swirlers can only be produced by Additive Manufacturing. The benefits of using Additive Manufacturing are lead time reduction & life time improvement for complex parts and energy increase through practically unlimited options for internal and external cooling duct design.

Also for new energy sectors 3D-printing may bring benefits. According to MIT 3D-printed solar panels could be roughly 20% more efficient than flat solar panels. Some raw materials used to make flat solar panels include glass, polysilicon and indium. These are expensive and they end up costing more when a significant fraction is lost as “waste” in traditional manufacturing. The radically more efficient and precise 3D-printing manufacturing method could cut production costs by as much as 50 %. These savings can then be passed on to the consumer, making the switch from fossil fuels to solar energy more appealing than ever. Australian scientists even dream of developing 3D-printed organic solar cells capable of powering a skyscraper. 3D-printing can produce extremely thin solar cells which can be printed on untreated paper, plastic or fabric rather than expensive glass. Therefore the advanced ability to create flexible solar panels at a lighter weight could have big positive implications for wearable hi-tech clothing, radios and future electronics. The big advantage is that the panels can be produced on the spot of demand and so lead to important savings in shipping costs.

Selective Laser Sintering can be used for the fabrication of micro fuel cells. The method opens up the capability of ultrafast prototyping, as the whole device can be produced at once, starting from a digital 3D model. Other interesting applications in new energy sectors are small-scale 3D-printed wind turbines, and Pelton turbines for small-scale hydropower experiments.

There is also some research going on concerning 3D-printing applied to nuclear and fusion power components.

2.10 Construction

Research related to the use of 3D-printing in construction started at the University of Southern California, where a concept called Contour Crafting was developed, as well as at Loughborough University, where a similar approach was simultaneously developed: concrete printing. There are currently quite a lot of activities in this area conducted in many countries (e.g. China, Australia, US, Netherlands, France, Finland etc.). However, if we look at activities purely related to construction (thus excluding applications like furniture and lightning) they are not yet commercialised but many of them are in a demonstration phase. However, the example of senior architecture lecturer Dr. Hank Haesuler for the University of New South Wales claims that “*in five to ten years we will see more and more 3D-printed housing construction and nodes*”, suggesting that room is still left to further development.

The construction industry can be understood as the industry concerned with the creation and building of facilities and structures as well as underlying processes. The industry size is six to nine percent of the gross domestic product of developed countries. There are three main drivers to adopt 3D-printing technologies in the construction industry: to build more affordable houses, to build on-the-spot emergency houses as well as to increase architectural flexibility. These drivers are somewhat contradictory and thus are approached differently. The affordability approach is usually based on a higher automation as well as redundancy of formworks, scaffolds and similar. Perrot et. al (France) claims that formwork represents 35-60% of the overall costs of concrete structures. However, to be affordable, the technology has to be fast as well, and that usually reduces the achieved quality in 3D-printing, which might cause some challenges. In the case of emergency houses the quality requirements are clearly lower, thus making it possible to really speed up the process. For instance, researchers of the University of Nantes in France are working with a concept based on a target which is to build emergency houses in just twenty to thirty minutes. The size of these “shelters” is 3 meters high by 3 square meters, and shelter is sealed and insulated.

In addition to approaches where whole houses are built, there are several activities going on to develop modular systems to build them, e.g. to 3D-printed “bricks” or walls modules. The Chinese company Zhuoda Group has filled 22 patent applications related to their module house concept, where the modules are printed elsewhere and then shipped to building location for final assembly.

Lux Research divides this sector in four groups according to technology maturity (i.e. Concept, development, showcase and commercial). According to Lux, the nearest commercial maturities are glass, lighting and furniture applications. However, in this context we classify these applications under consumer life style. The concept level includes framework, foundation and flooring, the development level includes exterior and interior walls and heating, ventilation and air conditioning (HVAC) systems.

Technology-wise, construction 3D-printing differs from other sectors, since it is somewhat based on different technologies than other sectors, or at least requires the development of new types of and bigger printers. Also materials differ from other areas (like concrete). In addition to approaches related to house building, there are projects to build e.g. bridges (in Netherlands).

2.11 Military

The applications in the military sector overlap with other sectors, such as healthcare, and aerospace. A very important application is printing of spare parts on the spot of demand. Some examples are printers on ships, and printing spare parts for fighters during maintenance on the ground. In remote areas it is possible to print temporary housing.

In addition to mobile factories also field hospitals are of interest to defence forces. One example under development is printing skin cells onto burn wounds.

2.12 Transportation (Marine & Special vehicles)

In offshore transportation the weight has not been a critical aspect such as in aero-transportation. However, this year we heard about several research investments to develop the use of 3D-printing in this sector as well. For instance, Hyundai Heavy Industries has invested in South Korea in an innovation centre which focuses on the use of 3D-printing in the marine industry. In the Netherlands, a consortium of 27 companies in the marine industry has kicked of a new project focusing on the 3D-printing of spare parts for the marine industry. Currently, it is difficult to get detailed information about the potential applications.

2.13 Food

3D-printing of food products has started from very 'niche' applications such as by e.g. university students conducting small projects. However, currently there are first commercialized chocolate printers being made available and some experts from the Institute of Food Technologists (IFT) predicts that 3D-printers have the potential to revolutionise the way food is manufactured within the next 10 to 20 years. The world first 3D-printed food conference was organised this year (2015).

In addition to providing new shapes, 3D-printing could offer some other benefits to food processing. In principle, one could produce customised food for various groups with different nutrient contents, e.g. different food for athletics and different food for pregnant women. It should also be possible to customise/personalise structures and flavours. In addition to these drivers, one additional aspect is to make food in remote locations.

The 3D systems chocolate printer was launched in 2014 and there are many others available as well. They are mainly targeted to homes and small cafes. The Albert Hejin supermarket in Eindhoven has started offering chocolate 3D-printed decorations on cakes. And it may be the first commercial venue (certainly the first large supermarket) to do so. In addition to chocolate, there are printers (however, some of them still under research) for sugar, ice-cream, pizza, pasta, vegetables, pancake, lollipops, chewing gum, etc. There are also various concepts developed for manufacturing of whole dishes. For instance, the MIT has launched a whole machine concept for this purpose.

2.14 Miscellaneous

In addition to the above mentioned sectors and related applications, there are various miscellaneous applications, where 3D-printing is also used or planned to use. Probably the most interesting and potential applications are found in the area of optics. There are e.g. approaches to print glass, or plastics with good optical properties (i.e. print lenses, optical fibres etc.). Final usage of these products will probably be observed in some other industrial areas. There are also various examples of 3D-printing in the entertainment industry. Movies, games, adult entertainment and other similar sectors have several examples of using 3D-printing to make e.g. personalised products or to speed up e.g. digitalisation of various objects. The software industry is also indirectly affected by 3D-printing, since new softwares are needed e.g. to make better models (CAD) or modify existing ones.

3/ Quantitative analyses and Sectors-Applications Matrix (SAM)

3.1 Patent data analysis

3.1.1 Approach

The patent analysis was conducted as complementary search strategy to identify innovative industrial players across Europe. The number of patents and the time since their official filing served as indicators for the significance of the firm. The patent analysis particularly allowed for the identification of the supply side of 3D-printing (=supply-capabilities), i.e. producers of equipment, material, facilities, etc.

In order to identify potential industrial players with technologies related to 3D-printing technologies we first conducted a small search to identify any relevant specific studies and analysis using patents and identified a few very recent studies relevant to our work. However, care has to be taken with comparing the different patent data analyses, as they encompass very different search strategies or analyse different time periods[319]. A study by the patent search institute Gridlogics (2014) in particular comprised the scope of our study. This study identified patents in the field of 3D-printing between 1990 and 2014 and hence we used the results of this work. In addition, a study by the IPO served as interesting source to identify relevant industrial players. However, as these studies only analysed patents until 2013 we conducted an additional patent analysis based on the EPO database. Furthermore it is also of interest that from 1st January 2015 a new patent subclass was introduced by the WIPO (World International Property Organisation) specifically dealing with Additive Manufacturing (see Box 29).

Box 29: Patent class Additive Manufacturing

B33Y ADDITIVE MANUFACTURING, i.e. MANUFACTURING OF THREE-DIMENSIONAL [3-D] OBJECTS BY ADDITIVE DEPOSITION, ADDITIVE AGGLOMERATION OR ADDITIVE LAYERING, e.g. BY 3-D PRINTING, STEREOLITHOGRAPHY OR SELECTIVE LASERSINTERING This subclass covers: Technologies involving the use or application of processes or apparatus that produce three-dimensionally shaped structures by selectively depositing successive layers of material one upon another. In particular it covers processes, apparatus, materials, and other aspects of additive manufacturing, i.e., making, repairing, or modifying articles of manufacture by the selective solidification of material onto a substrate or previously developed layers, for example, by selective sintering of a particulate.

Obviously, this subclass alone is not sufficient for analysis, as it will take some time to add this classification number to patents submitted before this date. However, the analysis of the new patent class B33Y Additive Manufacturing on the EPO database revealed that until end of August 2015 no patent have been published so far.

Special attention was paid to the problem of intellectual property rights of 3D-printing. The Intellectual Property Office commissioned an evaluation of the development of the 3D-printing sector. The executive summary presents the implications for intellectual property law, a quantitative analysis of online distribution of 3D-printing files and summarises a series of cases studies on the role of 3D-printing in key sectors. As the 3D-printing market grows, there is evidence of intellectual property infringement, at present on a small scale. The interest and activity is growing every year. This highlights the potential for future intellectual property issues[320].

3.1.2 Results

Findings of the two most relevant patent analyses will be summarised in this chapter along with updated data from our own investigation. The respective search algorithms are summarised in annex. The results of these analyses were added to the Systems-Application Matrix (see Section 3.4 of this report).

[319] Wohlers Report 2015: Trends. Analysis. Forescast. 3D-printing and Additive Manufacturing. State of Industry. ISBN 978-0-9913332-1-9 Intellectual Property Office, 3D-printing: A Patent Overview (Newport: Intellectual Property Office; November 2013) https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/312699/informatics-3d-printing.pdf 3D-printing: Technology Insight Report (2014)¸ Gridlogics Technologies Pvt Ltd; http://www.patentinsightpro.com/techreports/0214/Tech%20Insight%20Report%20-%203D%20Printing.pdf

[320] A Legal and Empirical Study into the Intellectual Property Implications of 3D-printing: Executive Summary; Published by The Intellectual Property Office March 2015; ISBN: 978-1-908908-85-8; https://www.gov.uk/government/publications/3d-printing-research-reports A Legal and Empirical Study of 3D-printing Online Platforms and an Analysis of User Behaviour; Published by The Intellectual Property Office March 2015; ISBN: 978-1-908908-96-4; https://www.gov.uk/government/publications/3d-printing-research-reports The Current Status and Impact of 3D-printing Within the Industrial Sector: An Analysis of Six Case Studies; Published by The Intellectual Property Office March 2015; ISBN: 978-1-908908-86-5; https://www.gov.uk/government/publications/3d-printing-research-reports Bradshaw, S., Bowyer, A. and Haufe, P., 2010. The intellectual property implications of low-cost 3D-printing. ScriptEd, 7 (1), pp. 5-31.

Table 16 shows the top patent applications in the field of 3D-printing. Some of the top applicants, such as Fujitsu and NEC, have been involved in the patenting of 3D-printing-related technologies for over 20 years. However, when analysing the data closer, it is evident that this company (Fujitsu) has not been active in this area for some time and that the granted patents owned by Fujitsu will soon expire, for that reason Fujitsu does not appear in analyses of recent data among the top companies. In contrast, some of the other top applicants, such as Stratasys and Corp Z, have filed for patents in this area only relatively recently. Some applicants have entered the technology space (e.g. Objet Geometries since 1989) later on and others have stopped patenting in the field (e.g. LG Phillips after 2004), explaining part of the difference in the lists of top companies.

Both Stratasys and 3D systems did not apply for any patent until 1993 and 1990 respectively. Stratasys did not start up until 1989 and was floated on the stock market in 1994. Stratasys has merged with Objet and MakerBot Industries so that the patents owned by both these companies were transferred to a single company which lead to the highest in the dataset as analysed by Gridlogistics. 3D Systems was founded in 1986 with a rapid acquisition process merging with Z Corp, and Vidar systems amongst others.

Table 16: Top patent companies with 3D-printing patents (European Companies in cursive)

Patent Assignees (Gridlogics[321]) 1990-2013	Total No. of Published Patents	Patent Assignees (IPO[322]) 1980-2013	Total No. of Published Patents
3D Systems Inc	39	3D Systems Inc[323]	91
Stratasys Inc	37	Stratasys Inc [324]	92
Massachusetts Inst. Tech	30	Fujitsu Ltd[325]	92
Hewlett-Packard Co	26	NEC Corp	67
Hitachi Chem. Co Ltd	26	Samsung Electronics Co Ltd	48
Matsushita Electric Works Ltd	24	*LG Phillips LCD Co Ltd*	41
Therics Inc	23	Object Geometries Ltd	38
Materialise NV	22	Univ. Texas System	36
Objet Ltd	20	Boeing Co	34
Panasonic Corp	20	Z Corp	34
IBM Corp	19		
The Boeing Co	19		
Mimaki Engg Co Ltd	17		
3Shape A/S	15		
Dainippon Printing Co Ltd	15		

Source: Gridlogics (2014), IPO (2013)

321 3D-printing: Technology Insight Report (2014)¸ Gridlogics Technologies Pvt Ltd; http://www.patentinsightpro.com/techreports/0214/Tech%20Insight%20Report%20-%203D%20Printing.pdf

322 Intellectual Property Office, 3D-printing: A Patent Overview (Newport: Intellectual Property Office; November 2013) https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/312699/informatics-3d-printing.pdf

323 3D Systems has merged with Z Corp, and Vidar systems amongst others, the patents were added up in this study.

324 Stratasys has merged with Objet and MakerBot Industries, the patents were added up in this study

325 Fujitsu has not been active in this area for some time, though, the granted patents owned by Fujitsu will soon expire.

Table 17 depicts the results of the patent analysis in the most recent years between 2014 and 2015 based on an analysis of data from the EPO. Of particularly interest is that some European firms in the Aerospace sector (Rolls-Royce, BAE Systems, Airbus, SNECMA) have successfully granted patents in 3D-printing and hence obviously European companies have caught up in the international competition. Materialise N.V. is a Belgium based company with more than 1200 employees worldwide specialised in all fields of 3DPrinting, ranging from software (i.materialise.com) to Biomedical Engineering and Additive Manufacturing Services of prototypes and everyday objects. Alstom Technology Ltd is applying Additive Manufacturing techniques for gas turbines and power supply. DSM IP Assets B.V. delivers innovative solutions that nourish, protect and improve performance in global markets such as food and dietary supplements, personal care, feed, medical devices, automotive, paints, electrical and electronics, life protection, alternative energy and bio-based materials with a focus on engineering plastics. Michelin has for several years been developing its unique expertise in metal Additive Manufacturing in order to produce, on an industrial scale, mould parts that are unachievable using traditional means of production (machining, welding, etc.). Michelin has only very recently (September 2015) joined up with Fives to form FIVES MICHELIN ADDITIVE SOLUTIONS offering industrialists different areas of application (such as automotive, aerospace, health, etc.), a complete solution from the design and manufacture of machines and complete production lines to the related services (redesign of parts, definition of the manufacturing process, installation, production support, training, etc.).[326] The aim of Blueprinter ApS in Denmark is to develop an easy to use 3D-printer affordable even for very small businesses. The Dutch LUXeXcel Holding B.V. focuses on optics and consumer products, as stated on their homepage "transparent 3D-printing service, customisation for optics and products that require the highest standard in transparency". Siemens AG is interested in applications of 3D-printing for Healthcare, Energy and Electronics.

Table 17: List of top companies (2014 - 2015) (European companies in cursive)

Company Name	Patent Assignees 2014-2015
Rolls-Royce	11
Samsung Electronics Co Ltd	11
Honeywell International Inc.	10
Stratasys Inc	8
Airbus	7
BAE Systems PLC	7
Materialise N.V.	7
Alstom Technology Ltd	6
GENERAL ELECTRIC COMPANY	6
Panasonic Corporation	6
DSM IP Assets B.V.	5
Hamilton Sundstrand Corporation	5
LG Chem, Ltd.	5
Michelin	5
SNECMA	5
3D Systems Incorporated	4
3M Innovative Properties Company	4
Blueprinter ApS	4
FUJITSU LIMITED	4
LUXeXcel Holding B.V.	4
SIEMENS AKTIENGESELLSCHAFT	4

Source: EPO, own calculation

The activities of the companies identified by the patent studies and analysis were analysed in more detail and information were added into the SAM.

326 FIVES MICHELIN ADDITIVE SOLUTIONS will be 50% owned by Fives and 50% by Michelin and will benefit from a financial contribution of at least €25 million in the first three years. http://www.fivesgroup.com/news-press/news/the-michelin-group-and-fives-join-forces-and-create-fives-michelin-additive-solutions-to-become-a-major-metal-3d-printing-player.html

3.2 Analysis of FP-funded projects

3.2.1 Approach

As a basis for the identification of relevant actors and application fields the EUPRO database was used. This database contains comprehensive, systematic and revised information on more than 60,000 research projects (title, content, duration, cost, etc.) and their participants (name, type of organisation, location, contact person, etc.) from the first to the seventh EU Framework Programme. Projects from Horizon 2020 were added by direct search in the on-line Cordis[327] database. In order to identify EU projects dealing with 3D-printing and Additive Manufacturing the following key words were used:

- "*3D-print*"
- "*three dimensional print*"
- "*additive manufac*"
- "*electron beam melting*"
- "*selective laser melt*"
- "*selective laser sinter*"
- "*fused deposition modelling*"
- "*fused deposition modeling*"
- "*stereo lithogra*"
- "*stereolitho*"
- "*three dimensional biopr*"
- "*Bioprint*"
- "*drug print*"
- "*binder jetting*"
- "*material jetting*"
- "*sheet lamination*"
- "*laser cusing*"
- "*direct metal laser sintering*"
- "*food print*"

The results were supplemented with further input from experts[328] and official information from EU websites. Within the resulting projects irrelevant projects, e.g. only dealing with 3D scanning or just mentioning 3D-printing as one of many possible methods without applying it within the project, were eliminated. Table 18 provides an overview of the total number of relevant projects and the number of participants under each Framework Programme (FP).

Table 18: Overview of projects dealing with 3D-printing in the EU Framework Programmes

EU Programme	Number of projects	Number of participants
INTAS[329]	3	20
FP4	10	105
FP5	4	16
FP6	11	149
FP7	64	553
Horizon 2020	9	55**
Total	**101**	**602**

** The total number of participants eliminates partners that participated in different frame programmes*
***H2020 is not completed yet in partner participations*

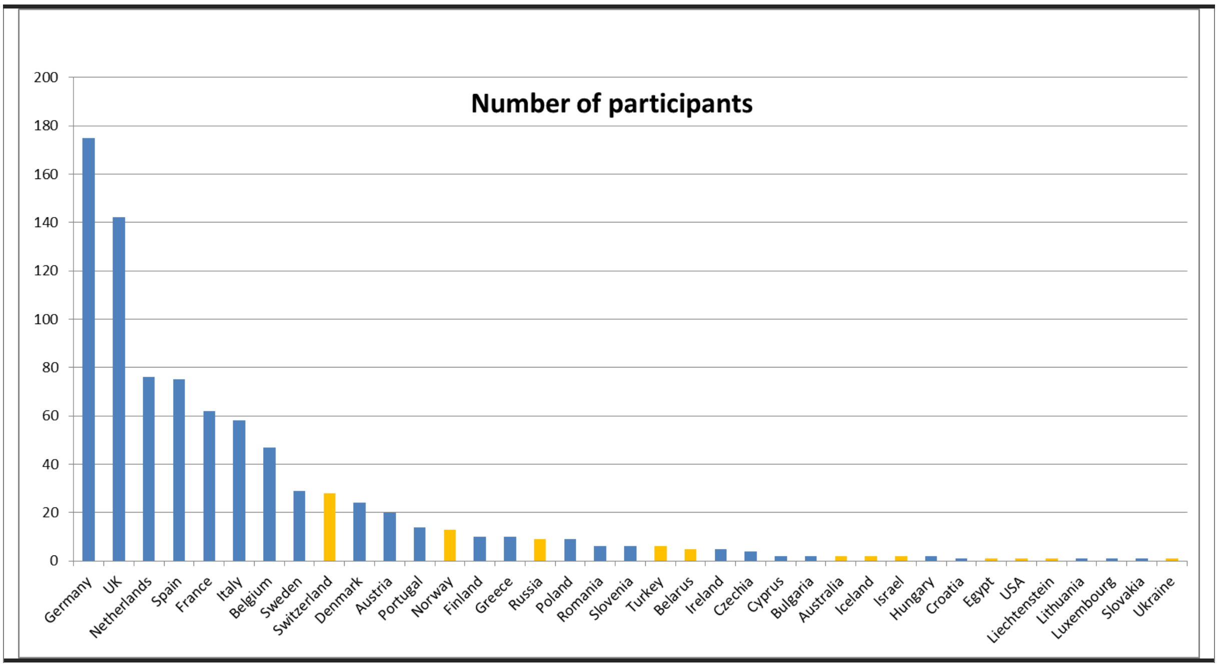
Source: EUPRO database, CORDIS database, own calculation

[327] http://cordis.europa.eu/search/advanced_de?projects
[328] The European Commission (RTD D.2) provided us with a list of EU projects dealing with 3DP which complemented particularly the results of the most recent projects funded within H2020.
[329] INTAS is an international association which promotes co-operation with scientists in the NIS, and complements the activities of Copernicus-2. It was set up in June 1993 as an independent organisation under Belgian law, and its members currently comprise the European Community, the EU Member States, Iceland, Israel, Latvia, Norway, Romania, Slovenia and Switzerland. As a non-profit, charitable association, based in Brussels and tax exempt, it is funded primarily through the Fifth Framework Programme, and carries out a large part of EU research activities with the NIS. https://ec.europa.eu/research/nis/en/intas.html

3.2.2 Results

101 projects were identified following the search strategy described above. A comprehensive list of these projects was added to the appendix of this report. Most project partners came from Germany, UK, the Netherlands, Spain and France (see Figure 28) and companies and research organisation with the most involvement in EU Framework Progammes are depicted in Figure 28. The 11 organisations with most projects (5-25) in the field of 3D-printing were evaluated in more depth. A cross table to investigated the relationship of these organisations can be found in annex as well. Information relevant to the thematic analysis was then added to the Sector Application Matrix.

Figure 28: Statistical overview of country participation in EU framework programmes



Source: EUPRO database, CORDIS database, own calculation

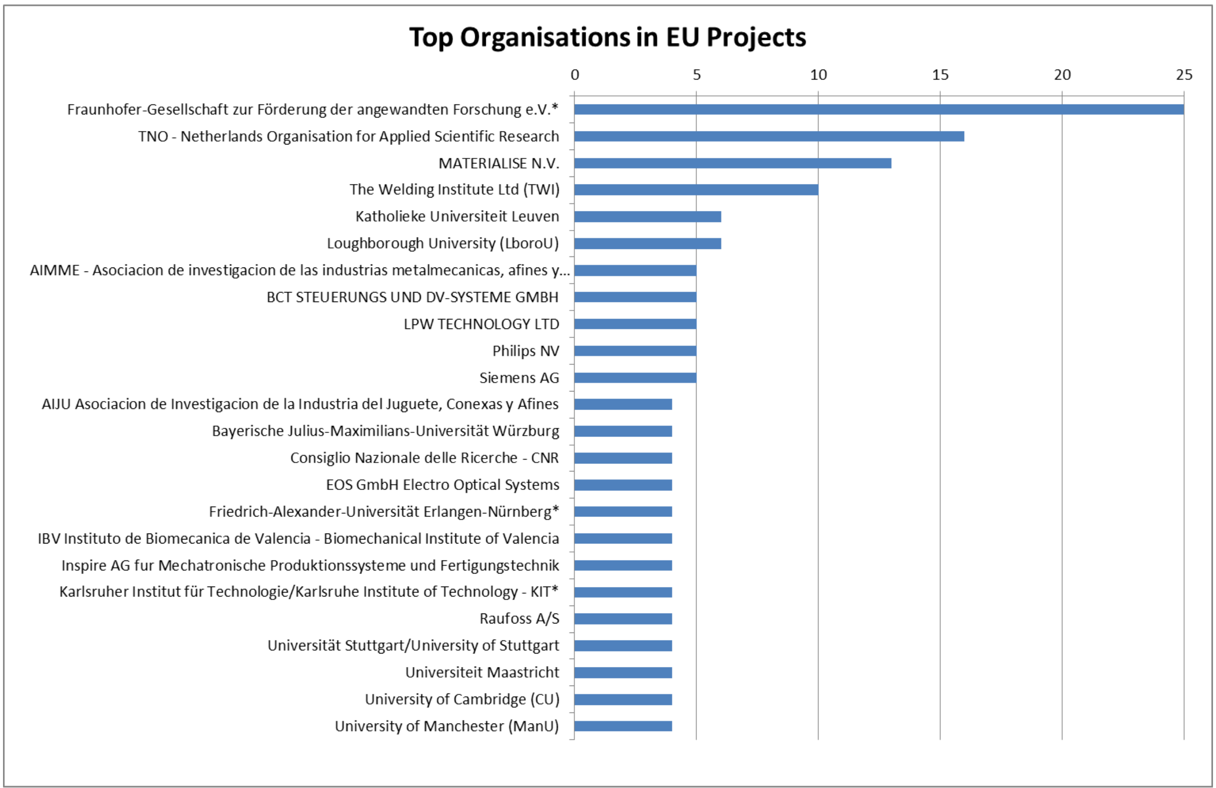
Of all research organisations the German Fraunhofer Gesellschaft zur Förderung der angewandten Forschung e.V. research institute was most active, being involved in 25 projects (20 of them in FP 7), collaborating with most of the other top 11 organisations except the Spanish AIMME and AJUI. Their projects focused on metal and ceramic and multi-material components, construction of light weight design for e.g. aeronautic or automotive applications, medical implants and micro mechatronic components as well as new smart manufacturing systems.

Apart Fraunhofer Research Institutes the most active German Universities and research organisations were Universities Würzburg, Nürnberg or Stuttgart and the Karlsruhe Institute of Technology KIT. In Germany many companies were involved in European projects, from large companies such as Siemens, BMW, EADS or Lufthansa, to small and medium companies. Siemens is a leading supplier of systems for power generation and transmission as well as medical diagnosis, all within the focus of their project topics.

BCT Steuerungs und DV-Systeme GmbH participated in 5 EU projects in the 7th framework programme, specialises in solutions for in-process scanning and adaptive machining to create automated complete solutions by linking single systems. BCT has many years of experience in the use of CAD/CAM/NC together with measuring and manufacturing methods working together with both users and manufacturers of machines, controls and sensors.

EOS GmbH Electro Optical Systems focuses on high-end Additive Manufacturing (AM) solutions applying amongst others Direct Metal Laser Sintering (DMLS™) technology. Projects involved ceramic applications and Additive Manufacturing of tiles as well as projects to along the supply chain to strengthening the industries competitive position based on on-demand production.

Table 19: Organisations with most involvement in EU framework programmes (25-4 projects)



Source: EUPRO database, CORDIS database, own calculation

In the UK apart from the research conducted at Loughborough and Cambridge University the strongest companies or better private research institutes were The Welding Institute (TWI) and LPW Technology Ltd. TWI is an independent research and technology organisation, with expertise in materials joining and engineering processes applied to industry. LPW Technology Ltd. was originally established to provide application support and powders to users of Laser Deposition and Powder Bed/Additive Metal Manufacturing machines. Both companies participated in projects dealing with Selective Laser Melting, mainly with metal as well as material for light weight components and past production along the supply chain.

In the Netherlands the strongest partners were TNO, an independent non-profit research organisation and Philips N.V. TNO took part in a wide range of projects, coordinating three of them. Subjects of these projects were digital and personalised fabrication, supply chain management, customised medical implants and ortheses as well as micro-forming complex 3D and lightweight metal parts. Philips, being active in the areas of Healthcare, Consumer Lifestyle and Lighting, contributed to projects dealing with complex 3D parts, printing of electronics and organic materials and Graphene on a nanoscale basis.

In Belgium, Materialise N.V. participated in some of the same projects, with a main focus on software, rapid prototyping, Additive Manufacturing and biomedical engineering. *Materialise* is a spin-off of the KUL (Katholieke University of Louvain).

The most active research organisations in Spain were Metalworking Technology Institute, AIMME, AIJU Instituto Tecnológico de Producto Infantil y Ocio, and IBV, the Biomedical Institute of Valencia. With different foci the three research institutes participated in projects concentrating on metal working, applications for sports and leisure or biomedical applications.

Most active companies were further the Swiss INSPIRE AG is a strategic partner of the ETH Zurich, the leading Swiss competence center for technology transfer to the MEM industries, and Raufoss A/S, a company within the The Neuman Aluminium Group, specialised in the development and the production of high-quality aluminium parts A short description of the **biggest projects**, either in volume or in numbers of partners, is given next (see Table 20). A summary of research projects funded in FP6, FP 7 and Horizon 2020 of the most active research organisations can be found in the annexes.

Table 20: Overview of biggest EU-funded research projects and topics in line with the Applications of the SAM

Project	Sector and applications
AMAZE (**Additive Manufacturing A**iming Towards **Z**ero Waste & **E**fficient Production of High-Tech Metal Products); FP 7 ▶ The goal of AMAZE is to produce large defect-free additively-manufactured metallic components (up to 2 meters) <u>with close to zero waste</u> (50% cost reduction for finished parts) used in the high-tech sectors aeronautics, space, automotive, nuclear fusion and tooling. ▶ The commercial use of adaptronics, in-situ sensing, process feedback, novel post-processing and clean-rooms in AM will be reduced (quality levels are improved, build-rates increased by factor 10, dimensional accuracy increased by 25% and scrap-rates slashed to 5%) ▶ The links between alloy composition, powder/wire production, additive processing, microstructural evolution, defect formation and the final properties of metallic AM parts will be examined	▶ Aerospace: Component repairing ▶ Aerospace: Non-structural parts for aeroplanes ▶ Automotive: Non-structural parts
ARTIVASC 3D (**Arti**ficial **vas**cularised scaffolds for **3D**-tissue-regeneration); FP 7 ▶ ArtiVasc 3D will provide a micro- and nano-scale based manufacturing and functionalisation technology for <u>the generation of fully vascularised bioartificial tissue</u> that enables entire nutrition and metabolism. ▶ The bioartificial vascularised skin (engineered in ArtiVasc 3D) will allow tissue replacement with optimum properties. Vascularised skin will also be used as an innovative in vitro skin equivalent for pharmaceutical, cosmetics or chemical substance testing, which represents a promising method to reduce expensive, ethically disputed animal testing. ▶ ArtiVasc 3D will develop a combination of hi-tech engineering (micro-scale printing, nano-scale multiphoton polymerisation and electro-spinning) with biological research on biochemical surface modification and complex cell culture.	▶ Healthcare: Bioprinting / organ printing
BOREALIS (the 3A energy class Flexible Machine for the new Additive and Subtractive Manufacturing on next generation of complex 3D metal parts); H2020 ▶ Borealis project presents an advanced concept of machine for powder deposition Additive Manufacturing and ablation processes that integrates 5 AM technologies. The machine is characterised by a redundant structures constituted by a large portal and a small PKM enabling the covering of a large range of working cube and a pattern of ejective nozzles and hybrid laser source targeting a deposition rate of 2000cm3/h with 30 sec set-up times. Software infrastructure enables a persistent monitoring and in line adaptation of the process ▶ Aiming at TRL 6 for two complete Borealis machine in two dimensions – a lab scale machine and a full size machine – which are foreseen to be translated into industrial solution by 2019	▶ Machines & Tooling: Spare parts for machines ▶ Machines & Tooling: Proto-typing in product development of machines
CUSTOM-FIT (A knowledge-based manufacturing system, established by integrating Rapid Manufacturing, IST and Material Science to improve the Quality of Life of European Citizens through Custom fit Products); FP 6 ▶ CUSTOM-FIT drastically changes how and where products are designed and made. It creates sustainable, knowledge-based employment, which plays a critical role in safeguarding Europe's manufacturing industry by developing and integrating a completely new and breakthrough manufacturing process based on Rapid Manufacturing (RM) ▶ Three main technical breakthroughs: Automated design system for knowledge based design of Custom-Fit products, Processing of graded structures of different material compositions and Rapid Manufacturing for Instant and On-Demand manufacturing of graded Custom-Fit products. ▶ Enables a vertical integration in the value chain and horizontal integration by the ability to transfer the knowledge to other industrial sectors.	▶ Machines & Tooling

Project	Sector and applications
NAIMO (NAnoscale Integrated processing of self-organizing Multifunctional Organic Materials); FP6 ▶ NAIMO will develop new multifunctional materials that are processed by solution-based Additive Manufacturing (e.g. direct printing), under quasi-ambient conditions, to form a composite material with designed multifunctionality in an environmentally-friendly way. ▶ A key outcome of NAIMO will be the set of materials, process and manufacturing capabilities to transform a plastic film substrate into a multifunctional composite (with designed electronic, optical, sensing and magnetic capabilities).	▶ Healthcare

3.3 Bibliometric analysis

3.3.1 Approach

Scientometric and bibliometric methods can serve as a valuable tool for gaining an overview on a research topic and insight into scientific literature and to identify relevant key players (both academic and industrial research players, top researchers and the connections between them).

Scientific activity and the associated research output are reflected in the number of scientific publications issued worldwide in any field of research. Consequently, high numbers of scientific papers on a particular technology in a certain area indicate high scientific activities and specialisation in this area, whereas low activities may result in technological dependencies on other regions concerning the particular technology. Beside the identification of topics and key players, we analysed the network and connections between topics or actors, thus identifying related topics or collaboration between organisations. The benefit of bibliometric analysis refers to the possibility of content-based structuring of information, the identification of subtopics, the visualisation of the contents, of structure and connections of information. The calculations were done with the tool BibTechMon^{TM} developed by AIT.[330]

The computation of science maps is based on the two dimensional representation of the co-occurrence matrix of terms in the relevant literature (reviewed journals, conference proceedings, patents). The representation of the inter-term relations is done via a spring model and by clustering algorithms. Depending on the question of investigation, the map renders descriptors (keywords), extracted noun phrases (e.g. extracted from Abstracts and titles), actors (authors, organisations) or a combination thereof. By defining appropriate indicators, it is possible to **identify emerging research** fields or **emerging or incumbent key players in the relevant scientific communities**.[331]

The basis of the analysis was data from the Web of Science^{TM} publication database from Thomson Reuters.[332]
We adopted the following search strategy for the time period 2010 until 09th July 2015:

- Topic=(3D-print* OR three dimensional print* OR 3D plot* OR additive manufac* OR stereolitho* OR stereo lithogra* OR direct metal laser sinter* OR drug print* OR 3d Biop* OR three dimensional biopr* OR electron beam melting OR Selective laser melt* OR Selective laser sinter* OR fused deposition modelling OR fused deposition modeling OR Laser cus* OR sheet lamination OR binder jetting)
- AND Document Type = (Article OR Book OR Book Chapter OR Meeting Abstract OR Meeting Summary OR Proceedings Paper OR Review)

By employing this search strategy we were able to identify and analyse 4,713 recorded articles. Using the BibTechMon^{TM} software we were able to calculate networks based on co-object analysis; the research activity was measured by weighted number of local agglomerated similar publications; similarity measured by the Jaccard index of bibliographically coupled publications, visualisation was performed with a spring model and number weighted by the similarities between publications. Some results of the analysis are presented next. In addition, we incorporated findings within the Sectors-Application Matrix.

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330 Kopcsa A, Schiebel E. (1998). Science and Technology Mapping: A New Iteration Model for Representing Multidimensional Relationships. Journal of the American Society for Information Science, 49, 1, 7-17.

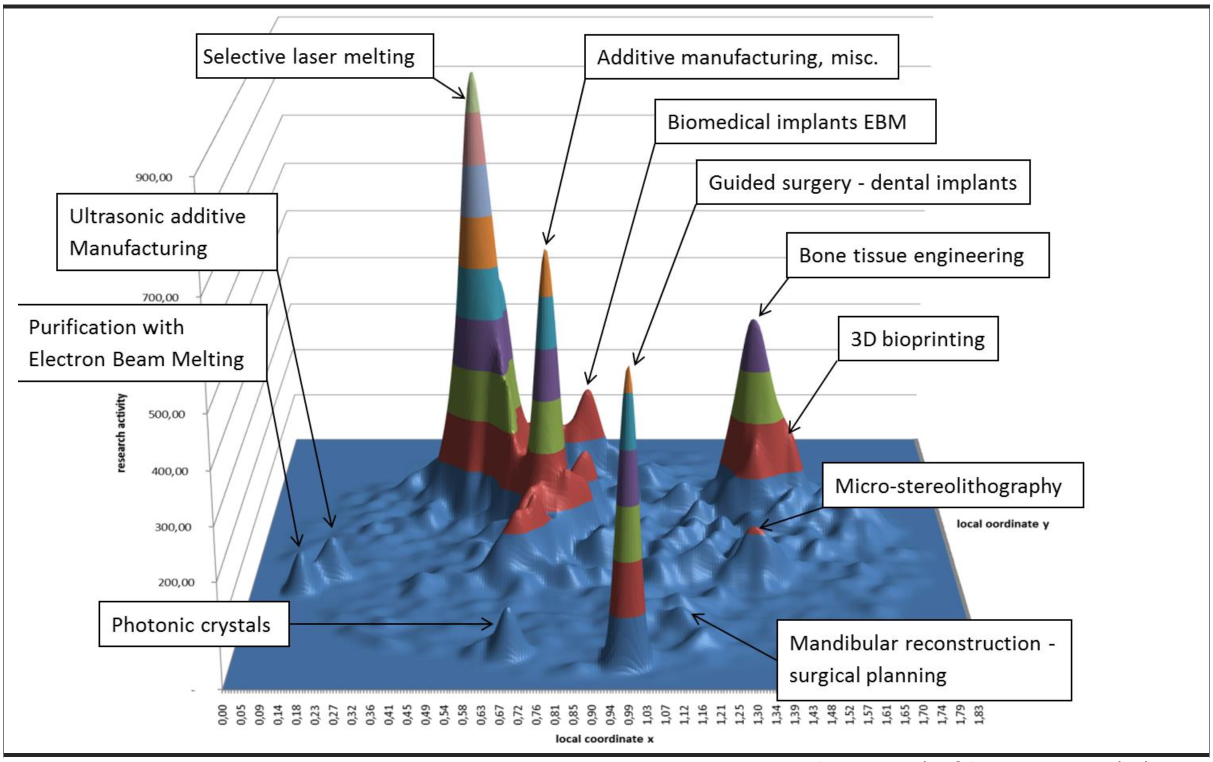
331 In case of this literature analysis an object (a node) is a paper. The "size" of a node is related to the number of cited references used in this paper. The more references a paper cites, the "bigger" the node is. Two papers share an edge if they cite the same reference. The more references two papers share, the closer they are related and thus are drawn together closer in the network. The nodes find their positions in the network graph based on their relations to all other nodes. This results in a network of nodes, where clusters of nodes dealing with similar topics are formed. Papers lying within these clusters can be studied whereby topics are identified and labelled. This results in a map of research areas and topics, with research fronts, clusters of highly cited papers, standing out.

332 The Web of Science^{TM} is an online database and provides a citation databases and covers over 10,000 of the highest impact journals worldwide, including Open Access journals and over 110,000 conference proceedings with the focus on essential data across 256 disciplines.

3.3.2 Results

Figure 29 depicts the scientific publication network where the height of peaks corresponds to the number of publications in a given field. The position of themes to each other is an indicator for how close or unrelated topics are. In total, we identified 11 peaks which are interpreted as research fronts.

Figure 29: Main research activities in 3D-printing and Additive Manufacturing



Source: Web of Science, own calculation

Table 21 summarises the distribution of publication numbers between continents. The number of publications is an indicator of how active research or industrial organisations are in each of the specified topics. In Europe the most outstanding topics of research were on "Biomedical Implants with Electron Beam Melting and Selective Laser Melting", "Mandibular Reconstruction Surgical Planning" and "Selective Laser Melting".

More detailed information was generated for each topic, i.e. research disciplines, keywords, pioneering publications, a list of most recent publications and key scientists with their respective affiliation. An example is given in annex for the research front "Micro-Stereolithography". In addition, the results of the analysis were further added to the Sectors-Application Matrix (see section 3.4).

Table 21: Distribution of Publications by Research Fronts and Continents (bold: strength of the EU)

Research Fronts	Africa	Asia	EU	Europe (without EU)	North America	Oceania	South America
3D Bioprinting		31	62	7	127	10	1
Additive Manufactured Scaffolds-Based Bone Tissue Engineering	1	106	76	10	53	6	5
Biomedical Implants EBM and SLM	1	37	**177**	10	65	8	3
Guided Surgery Dental Implants		22	96	21	25		17
Mandibular Reconstruction Surgical Planning	6	51	**113**	12	63	9	17
Microstereolithography		71	36	1	69	2	1
Photonic Chrystals Stereolithographie		31	2				
Additive Manufacturing, Misc.	1	14	54	5	24	2	6
Selective Laser Melting	5	150	**229**	17	34	3	
Silicon Purification By Electron Beam Melting		53					3
Ultrasonic Additive Manufacturing		4	6		41		
not assigned	45	1615	2127	243	1729	208	104
Sum	*59*	*2185*	*2978*	*326*	*2230*	*248*	*157*

Source: Web of Science, own calculation

For each of the identified topics the most active industrial companies were identified and shown in Table 22 with companies situated in Europe marked in grey[333]. Some selected findings for the three research fronts where Europe is particularly strong can be summarised as follows:

Biomedical, metallic implants fabricated with materials such as titanium, tantalum, chrome, cobalt and stainless steel have been in routine clinical use for several years. Medical grade Titanium alloys (Ti6Al4V) are widely used as implant materials due to their high strength to weight ratio, corrosion resistance, biocompatibility and osseointegration properties. The porous structures produced by the electron beam melting process present a promising rapid manufacturing process for the direct fabrication of customised titanium implants for enabling personalised medicine.[334] Most active companies in this research field were *3D Syst LayserWise, 3T RPD Ltd.; Avio SpA, Implantcast GmbH* and others, all with addresses in Europe.

Mandibular reconstruction is often needed after partial resection and continuity defect. The aims for reconstruction are the maintenance of proper aesthetics and symmetry of the face and the achievement of good functional result, thus preserving the form and the strength of the jaw and allowing future dental rehabilitation. Using Electron Beam Melting or Selective Laser Melting (SLM) is a rapid prototyping method by which porous implants with highly defined external dimensions and internal architecture can be produced. These methods for the processing of titanium have led to a one step fabrication of porous custom titanium implants with controlled porosity to meet the requirements of the anatomy and functions at the region of implantation.[335] Besides European *IVS Technology GmbH and Mat Dent NV* situated in Switzerland and Denmark most prominent companies were located in USA or China.

333 The analysis of organizations is demanding as the spelling and notation of an organization's name is not unique in the data source. Organizations may have changed their names or organization structures over the considered time span. Mergers and reorganizations of institutes and companies are not documented in the data sources. Therefore the available information of organizations in the specific data field was standardized manually. Even this work proofed to be a challenge. As countries have different institutional structures on universities for instance, as the department is quoted, sometimes a business unit, or the institute, and often it is not possible to decide about the hierarchical role of them. Nevertheless standardization was performed to show the visibility of the organizations. Therefore the reader is asked to take these preceding thoughts into account for considering the analysis of organizations.

334 Mróz W1, Budner B, Syroka R, Niedzielski K, Golański G, Slósarczyk A, Schwarze D, Douglas TE. (2015). In vivo implantation of porous titanium alloy implants coated with magnesium-doped octacalcium phosphate and hydroxyapatite thin films using pulsed laser deposition. J Biomed Mater Res B Appl Biomater. 2015 Jan;103(1):151-8. doi: 10.1002/jbm.b.33170. Epub 2014 May 7. Parthasarathy, J., Starly, B., Raman, S., & Christensen, A. (2010). Mechanical evaluation of porous titanium (Ti6Al4V) structures with electron beam melting (EBM). Journal of the Mechanical Behavior of Biomedical Materials, 3(3), 249-259. doi: http://dx.doi.org/10.1016/j.jmbbm.2009.10.006

335 Cohen, A., Laviv, A., Berman, P., Nashef, R., & Abu-Tair, J. (2009). Mandibular reconstruction using stereolithographic 3-dimensional printing modeling technology. Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology, 108(5), 661-666. doi: http://dx.doi.org/10.1016/j.tripleo.2009.05.023

Selective laser melting (SLM) is driven by the need to process near full density objects with mechanical properties comparable to those of bulk materials. During the process the powder particles are completely molten by the laser beam. The resulting high density allows avoiding lengthy post-processing as required with selective laser sintering (SLS) of metal powders. [336] Companies identified in this research fields were *EADS, LayerWise NV, Inspire AG* as well as *Robert Bosch GmbH and Siemens Turbomachinery AB*.

Table 22: Companies by research fronts – Authors' affiliations of type "company", European companies marked in blue

Name of Research Front	Most Active Companies
3D Bioprinting	NanotecMARIN GmbH, D-55128 Mainz, Germany
	Organovo Inc, San Diego, CA 92121 USA
	Stratasys Ltd, Rehovot, Israel
	TeVido BioDevices LLC, Austin, TX 78727 USA
Additive Manufactured Scaffolds-Based Bone Tissue Engineering	Biomatica Srl, Rome, Italy
	Hitachi Ltd, Hitachnaka Ibaraki 3128506, Japan
	Mo Sci Corp, Rolla, MO USA
	ReMeTeks Closed Corp, Moscow, Russia
Additive Manufacturing miscellaneous	Airbus Ltd, Bristol, Avon, England
	EADS Innovat Works Metall Technol & Surface Engn, D-81663 Munich, Germany
	EADS Innovat Works, Bristol BS997AR, Avon, England
Biomedical Implants EBM and SLM	3D Syst LayerWise NV, B-3001 Leuven, Belgium
	3T RPD Ltd, Newbury RG19 6HD, Berks, England
	Avio SpA, I-10040 Turin, Italy
	Ctr Sviluppo Mat SpA, I-00128 Rome, Italy
	Implantcast GmbH, D-21614 Buxtehude, Germany
	LayerWise NV, B-3001 Heverlee, Belgium
	LayerWise NV, B-3001 Leuven, Belgium
	Lima Corp, Milan, Italy
	Simpleware Ltd, Exeter EX4 3PL, Devon, England
	SLM Solut GmbH, D-23556 Lubeck, Germany
	Stanmore Implants Worldwide Ltd, Elstree WD6 3SJ, Herts, England
Mandibular Reconstruction - Surgical Planning	IVS Technol GmbH, Chemnitz, Germany
	Mat Dent NV, Dept Res & Dev, Louvain, Belgium
	Med Modeling Inc, Golden, CO USA
	Mitralign Inc, Tewksbury, MA USA
	Shanghai Dragon Automot Technol Co Ltd, Shanghai 201600, Peoples R China
	Shanghai ZhiZi Automot Co Ltd, Shanghai 201600, Peoples R China
	Siemens Healthcare, Cardiovasc MR R&D, Chicago, IL USA
Microstereolithography	AlpZhi Inc, Atlanta, GA 30318 USA
	Dow Chem Co USA, Elect Mat, Newark, DE 19713 USA
	GE Global Res, Niskayuna, NY 12309 USA
Selective Laser Melting	3DSIM LLC, Louisville, KY 40202 USA

[336] Kruth, J. P., Froyen, L., Van Vaerenbergh, J., Mercelis, P., Rombouts, M., & Lauwers, B. (2004). Selective laser melting of iron-based powder. Journal of Materials Processing Technology, 149(1–3), 616-622. doi: http://dx.doi.org/10.1016/j.jmatprotec.2003.11.051

Name of Research Front	Most Active Companies
	EADS Innovat Works Metall Technol & Surface Engn, D-81663 Munich, Germany
	Eurocoating Spa, I-38050 Cire Di Pergine, Trento, Italy
	INSPIRE AG Mechatron Prod Syst & Fertigungstech, IRPD, St Gallen, Switzerland
	INSPIRE AG Mechatron Prod Syst & Fertigungstech, Zurich, Switzerland
	Inspire AG, Inst Rapid Prod Dev, St Gallen, Switzerland
	K4Sint Srl, Pergine Valsugana, TN, Italy
	LayerWise NV, B-3001 Heverlee, Belgium
	LayerWise NV, B-3001 Leuven, Belgium
	Panason Corp Eco Solut Co, Kadoma, Osaka 5718686, Japan
	Polaronyx Inc, San Jose, CA 95131 USA
	Robert Bosch GmbH, Schwieberdingen, Germany
	Sichuan Petr Perforating Mat Ltd, Longchang 642177, Peoples R China
	Siemens Turbomachinery AB, S-61231 Finspang, Sweden
	SLM Solut GmbH, D-23556 Lubeck, Germany
	Units IM Technol AG, St Gallen, Switzerland
Silicon Purification by Electron Beam Melting	Baotou City Shansheng New Energy Co Ltd, Inner Mongolia, Peoples R China
	Grikin Adv Mat Co Ltd, Beijing, Peoples R China
	Qingdao Longsun Silicon Technol Ltd, R&D Dept, Qingdao 266000, Peoples R China
Ultrasonic Additive Manufacturing	Edison Welding Inst, Columbus, OH 43212 USA
	Solidica Inc, Ann Arbor, MI 48108 USA
Guided Surgery Dental Implants	*No companies were found in the data set analysed*
Photonic Chrystals Stereolithography	*No companies were found in the data set analysed*

Source: Web of Science, own calculation

3.4 Sectors-Applications Matrix (SAM)

The outputs of the first four tasks of the project were used as inputs to the Sectors-Applications Matrix presented below (see Table 23).

This matrix depicts every technology and associated geographical concentration, components of the European supply chain, the potential of the application area as well as its expected socio-economic impacts.

Table 23: Sectors-Applications Matrix

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Aerospace	**Structural parts for aeroplanes, especially engines (e.g. turbine blades, fuel nozzles)**	1-2	First components approved for commercial jet engines	EBM, SLM, DED	General Electric (GE Aviation / Morris Technologies), SNECMA, Hamilton Sundstrand, Boeing, Honeywell International Inc., Lockheed Martin,... CFM International (joint venture of GE & Snecma), Amaero (Australia)	AvioAero by GE Aviation (Turin/Milan), Rolls Royce, BAE Systems, Snecma (FR) ...	Airbus and its suppliers, Graphite Additive Manufacturing (UK), Avio (Italy), Arcam (Sweden)	B-to-B	Reduced costs, shorter lead time, reduced inventory costs, better performance, better quality, reduced buy-to-fly ratio	Special metal powders. Advanced materials.	Growing	Energy savings and emission reductions	Varetti, M.; Recent Achievement in Additive Manufacturing at Avio Aero. Additive Manufacturing for Defence and Airspace Europe Conference. 18.-19.2.2015, Lontoo. Slides, 16 p. http://www.fda.gov/downloads/MedicalDevices/NewsEvents/WorkshopsConferences/UCM418401.pdf 2.4.2015, http://www.merlin-project.eu/home/index.jsp, http://www.gizmag.com/ge-faa-3d-printing-aircraft-engine-part/37018
Aerospace	**Non-structural parts for aeroplanes (e.g. electrical boxes, brackets, air ducts)**	1-2	Have been used in military many years and increasing usage in commercial side	SLS, FDM, Material Jetting, SLM	Boeing, Stratasys, McDonnell Douglas	Airbus, Strasys europe	Airbus and its suppliers	B-to-B	Reduced costs, shorter lead time, reduced inventory costs, better performance, better quality, reduced	Advanced materials.	Growing	Energy savings and emission reductions	http://3dprintingindustry.com/2015/05/06/airbus-a350-xwb-takes-off-with-over-1000-3d-printed-parts/

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
									buy-to-fly ratio				
Aerospace	**Components for satellites (e.g. multifunction casing, RF filters, optical baseplate, bracket)**	1-2	Prototyping parts and various flight ready parts.	SLM, SLS	Lockheed Martin Space Systems, Boeing	ESA consortium	ESA coordinating actions with its suppliers	B-to-B	Reduction of cost, mass, lead time, and complexity of assemblies, high performance materials	E.g. carbon nanotube reinforced polymer (CNRP)	Growing	Energy, and material savings.	Williamson, M., Building a rocket? Press "P" for print... Engineering and Technology, March 2015, p. 40 - 43, ESA Roadmap, http://www.flightglobal.com/news/articles/lockheed-martin-reveals-f-35-to-feature-nanocomposite-357223/
Aerospace	**Component repairing, based on directed energy deposition and hybrid technologies (e.g. aircraft engine compressor components, blisks (intergrally bladed rotors), airfoils)**	1-2	Demonstrations	DED	Sciaky, Optomec, Lockheed Martin, …	Trumpf-Sisma, Fraunhofer ILT, Hermle (Germany), Wojskowe Zakłady Lotnicze Nr 2 (Polish aircraft repair company), UK Space Agency, Airbus…	E.g. Rolls-Royce Deutschland, Fraunhofer ILT; Zortrax, Poland (3D-printer manufacturer)	B-to-B	Cost and time savings, maintenance, security	Combination of materials possible	Growing	Material savings.	Nannan Guo et al, Additive manufacturing: technology, applications and research needs, Front. Mech. Eng. 2013, 8(3), 215-243. http://www.us.trumpf.com/nc/en/press/press-releases/press-release/rec-uid/267872.html..html, http://www.ilt.fraunhofer.de/en/publication-and-press/brochures/brochure_Repair_and_Functionalization.html

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Aerospace	**Components for very demanding environments (e.g. hypersonic flight systems, rocket propulsion systems)**	2-3	Under research	E.g. Binder Jetting (FEF)	USA (e.g. Missouri S&T for ultra high temperature ceramics)	ESA consortium	Does not exist.	B-to-B	Demanding environments, complex structures	E.g. ultra high temperature ceramics, refractory metals etc.	Growing	Development of material science	Nannan Guo et al, Additive manufacturing: technology, applications and research needs, Front. Mech. Eng. 2013, 8(3), 215-243.
Aerospace	**Fabrication of spare parts and satellites in spacecrafts and spacestations**	2-3	First componets have been printed	FDM, etc.	NASA consortium and ESA consortium	ESA consortium	Does not exist.	B-to-B	Avoiding launching from the earth	Depends on the application	Growing	Space utilization	http://3dprint.com/88514/made-in-space-and-nanoracks-sign-deal-to-build-and-deploy-cubesats-in-orbit/
Automotive	**Jigs and assembly tools (e.g. for in bodyshell construction, painting)**	1-2	Commonly used	SLS, FDM, SLM etc.	all leading manufacturers	e.g. Volvo, BMW, Audi	e.g. Volvo with Stratasys, Audi with Materialise	B-to-B	productivity, flexibility	tool steels	Tooling can have moderate impact		Günter Schmid and Ulrich Eidenschink, BMW Regensburg: WITH FDM IN JIG & FIXTURE CONSTRUCTION. Stratasys White paper.
Automotive	**Prototyping for product development (e.g. visual models, functional models for wind tunnel testing)**	1	Broadly used	various	all leading manufacturers	BMW, Audi (Lamborgini), Volvo, Fiat Chrysler,..		B-to-B	Faster product development, better performance, avoiding mistakes		Prototyping can have only limited impact		3D-printing from Stratasys and Energy Group Help Lamborghini Make Cars Faster. Davide Sher By Davide Sher On Tue, May 5, 2015

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Automotive	**Personalized car interiors (e.g. dashboard) and exteriors (e.g. wing mirrors and other non-sturctural components)**	1-2	At BMW, more than 100,000 parts a year are being made additively, according to Wolfgang Thiele, more than 95 percent of those are polymer-based interior and functional parts.	FDM etc.	e.g. BMW. Several Chinese companies (e.g. Shanghai Dragon Automot Technol Co Ltd) have wide patent portfolio	BMW, Ai Design (customized car manufacturer); Italy: Ferrari, Lamborghini, Agusta, Ducati; Mercedes,	e.g. BMW using stratasys technology, EOS, Additive manuf. Services: CRP Group, Skorpion, Energy Group and Proto Service	B-to-C	personalization, mass customization		Growing		https://www.stratasysdirect.com/case-studies/automotive-personalization-brought-to-life/
Automotive	**Demanding components (e.g. gear box, powertrain parts, water pump wheel)**	1-3	Under research / testing, e.g. in race cars, first parts approaching to commercial vehicles	SLM, SLS	e.g. BMW	BMW, Germany; Prodrive (UK); Fiat Chrysler Automobiles (FCA);	Michelin joint venture with Fives (metallic AM), France	B-to-C	better performance, complex structures		Growing, large and broad supply chain across Europe		Allen Kreemer, Stratasys, Inc. Motor Trends - Additive manufacturing drives production of race-ready parts. AM SRA. Wohlers 2015 - applications. http://www.metal-am.com/news/003245.html
Automotive	**Printed car body, chassis**	2-3			Local Motors (China)			B-to-C		e.g. CFRP, foams			https://localmotors.com/3d-printed-car/, http://www.techtimes.com/articles/67341/20150709/local-motors-unveils-the-design-of-highway-

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
													ready-3d-printed-car.htm
Automotive	**Light commercial vehicles (e.g. light weight parts, personalized parts)**	2-3	Toyota's highly customized i-Road Personal Mobility Vehicle, market launch 2016		Toyota (Japan), Jim Kor's Urbee (US)			B-to-C	Customization, personalization, light weighting			Energy savings and emission reductions	http://3dprintingindustry.com/2015/07/06/rinkak-provides-toyota-with-mass-3d-printing-for-i-road-project/
Healthcare	**Inert implants, hard implants i.e. bone replacement (e.g. acetabular implants, skull implants, sternum implants)**	1-2	More than 90 000 acetabular implants have been produced by AM, about half of them implanted. Some skull implants (polymer based) implanted succesfully. First sternum implant has been succesfully implanted (2015)		e.g. Oxford Performance Materials (US)	e.g. Symbios (UK), joimax (German), Layerwise (part of 3D Systems), Belgium, Nanotec Marin GmbH (Germany), Stanmore Implants Worldwide, 3T RPD Ltd, Implantcast GmbH, 3Dceram	WASP (Italy); Materialise (Belgium); Arcam AB (Sweden),	B-to-B, B-to-C	product customization and personalization, structural optimization (e.g. gradient structures), independence of economies of scale	Bio-compatible / bio-absorbable materials. Purity of materials	Growing, very innovate industry is emerging		Wohlers 2015. http://3dprintingindustry.com/2015/07/10/the-first-3d-printed-sternum-implant-deemed-a-success/, http://www.nanotecmarin.de/index.php/en/technologies

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Healthcare	**Tools, instruments & parts for medical devices (i.e. tools and jigs for surgery, i.e. Kelly hemostat, needle driver, tissue forceps, retractor, scalpel handle and Metzenbaum scissors) (eventually also consider exoskeletons)**	1-2	Major manufacturing technology for hearing aids, other areas growing or under research		Many US hearing aid manufacturers e.g. GN ReSound , 3D Systems, Medical Modeling,	Siemens, Lima Corporate (Italy), GN ReSound (Denmark), EnvisionTEC Germany, DSM	LayerWise, Belgium (advanced direct metal 3D-printing and manufacturing services); Materialise (Belgium); EOS, Germany; Ruetschi Technology AG (Switzerland), Concept Laser GmbH (Germany), EnvisionTEC with GN ReSound	B-to-B, B-to-C	more efficient production chain, mass personalization, remote operations	Bio-compatible materials	Growing		http://www.forbes.com/sites/rakeshsharma/2013/07/08/the-3d-printing-revolution-you-have-not-heard-about/

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Healthcare	**Dental (e.g. crowns, braces and dentures), also dental devices**	1-2	3D-printed dental guides. Indirect production of dental crowns	SLM, SLS	e.g. Align Technologies Inc (Invisalign Dental braces), DENTCA (USA), Stratasys (Israel/USA)	3DMedicalPrint, Austria; SLM Solutions Germany; EOS Germany; Concepts Laser Germany; Planmeca Group, Finland, Mat Dent NV, Implant & 3D Planning Ctr, Skyscan NV	Roboze, Bari Italy (High precision printer manufacturer)	B-to-B, B-to-C	Mass personalization, more effient prodution	Bio-compatible / bio-absorbable materials. Purity of materials	Growing, strong impacts		Economist: 3D-printing scales up, http://3dprintingindustry.com/2015/08/10/dentures-get-3d-printed-boost-with-dentcas-fda-approval/, http://www.3ders.org/articles/20140524-uk-dental-lab-plans-use-3d-printing-to-create-custom-made-spinal-implants.html
Healthcare	**Medical aids, supportive guides and prosthesis (e.g. facial prostheses, arm prosthesis)**	1-2	At least facial prosthesis manufactured commercially, others coming		Fripp design, UK (facial prosthetics)	e.g. Materialis, various DIY projects with service suppliers	Materialise	B-to-B, B-to-C	Mass personalization, more effient prodution	soft materials			Oliver Wainwright: Faces to order: how 3D-printing is revolutionising prosthetics. http://www.theguardian.com/artanddesign/architecture-design-blog/2013/nov/08/faces-3d-printing-prosthetics
Healthcare	**Prototyping i.e. preoperative models (prototypes based on scanning data)**	1	Increasingly used. From technological perspecive, the challenges are more related to		Various players	Various players e.g. Materialise, 3D Systems, Blueprinter	Materialise, Blueprinter	B-to-B, B-to-C	service, education, avoiding mistakes		Prototyping can have only limited impact		http://www.news-medical.net/news/20150803/3D-printed-models-of-childrens-brain-anatomy-help-reduce-operative-risk-of-complex-procedures.aspx

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
			scanning and other detection technologies, not to printing itself.										
Healthcare	**bioprinting, organ printing (e.g. human skin, blood vessels, kidney)**	2-3	Under research. Two-dimensional producs (like skin) will be first applications, followed by hollow tubes (blood vessels etc.) then hollow organs and finally solid organs. Scaffold is on approac, and might also been 3D printed.		e.g. Organovo (US), Wake Forest Institute of Regenerative Medicine (US), 3D biotek (US), Advanced biomatrix (US), TeVido BioDevices (US) several universities e.g. Wake Forest School of Medicine	regenHU Ltd (Switzerland), L´Oreal (France)	L´Oreal (France) with Organovo (US)	currently B-to-B, in future maybe B-to-C	personalization, productivity				e.g. Murphy and Atala – 3D bioprinting of tissues and organs, http://edition.cnn.com/2014/04/03/tech/innovation/3-d-printing-human-organs/, https://agenda.weforum.org/2014/08/3d-bioprinting-changing-medicine/, http://labiotech.eu/loreal-get-into-bio-printing-skin-for-cosmetic-tests/, http://www.technavio.com/blog/top-10-3d-bioprinting-companies, http://tevidobiodevices.com/

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Healthcare	**smart medicine (e.g. personalized dosage)**	1-2	First FDA approval for 3D-printed prescription drug (Aprecia, US). Under research		e.g. Aprecia, US			B-to-B, B-to-C	personalization, productivity				http://3dprintingindustry.com/2015/08/03/fda-approves-the-first-3d-printed-drug/
Machinery & Tooling	**Metallic mould inserts for injection moulding and die casting**	1	Commercially used, but not widely.	SLM, hybrid machines	Marketed strongly by Stratasys.	Major companies in different end-user sectors, e.g. automotive, consumer, aerospace, medical. Volvo Trucks (Lyon FR)	Some supplies exist, like Fado in Poland; Additive Industries (NL); Mcor, Ireland; EOS, Germany, InvisionTEC, Germany	B to B	High productivity and high quality through optimal cooling	New tool steels.	Growing, strong impacts on the value chain across Europe	Depends on application.	http://www.stratasys.com/solutions/additive-manufacturing
Machinery & Tooling	**Plastic mould inserts for injection moulding. Short series and prototypes for testing.**	1	Commercially used, but not widely.	Material jetting, SLS	Marketed strongly by Stratasys.	Major companies in different end-user sectors	Lot of suppliers.	B to B	Cutting costs and time.	Heat and wear resistant plastics.	Prototyping can have only limited impact	Depends on application.	http://www.stratasys.com/solutions/additive-manufacturing
Machinery & Tooling	**Sheet metal tools**	1	Commercially used, but not widely.	SLM. For short series and prototyping FDM, Material Jetting, SLS	Marketed strongly by Stratasys.	Major companies in different end-user sectors	Very often in house.	B to B	Cutting time.	New tool steels. Wear resistant plastics.	Tooling can have moderate impact	Depends on application.	https://www.stratasysdirect.com/blog/fdm-sheet-metal-forming/

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Machinery & Tooling	**Fixtures and jigs for assembly and welding**	1	Commercially used.	FDM, Material Jetting	Marketed strongly by Stratasys.	Major companies in different end-user sectors, e.g. in car industry.	Very often in house.	B to B	Cutting costs and time.	Cost and time cutting.	Tooling can have moderate impact	Depends on application.	http://www.stratasys.com/solutions/additive-manufacturing, http://www.stratasys.com/resources/case-studies/automotive/bmw
Machinery & Tooling	**Sand moulds and cores for foundries when individual castings are needed. Plastics patterns for sand casting.**	1	Commercially used by early adapter	Binder Jetting, FDM for pattern.	For sand moulds and cores: ExOne, headquarters in the USA. Stratasys active in marketing pattern making. Several players in US	For sand moulds and cores Voxeljet in Germany; Sand Made, Poland, Newbyfoundries, UK, 3Dealise Ltd UK	ExOne (The development and production facility in Augsburg, Germany)and Voxeljet supply services. Also other suppliers. Foundries. Several application industries.	B to B	Cutting time, reducing fixed costs, short series	Binders for moulds and cores	Growing, large and diverse supply chain acoss Europe	Depends on application.	http://www.stratasys.com/solutions/additive-manufacturing
Machinery & Tooling	**Patterns for investment casting for short series and product development.**	1	Commercially used.	Material Jetting, FDM	Marketed strongly by Stratasys.	Voxeljet in Germany strong in wax printers.	Often in house.	B to B	Cutting time.	PMMA, wax, SLA		Depends on application.	http://3dprintingindustry.com/2014/03/26/voxeljet-wax-investment-casting-process-3d-printing/, http://www.stratasys.com/solutions/additive-manufacturing

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Machinery & Tooling	**Spare parts for machines (e.g. gears, housings, buttons, fasteners)**	1-2	Cases exist, not in wide use yet (i.e. not provided as servive by OEM's)	Depends on application.	A wide sector: depends on application.	A wide sector: depends on application. Maersk, DK (Fabricate Spare Parts on Ships), online suppliers like Shapeways, iMaterialize and other AM service providers	A wide sector: depends on application.	(B to C), B to B	Cutting time, service business opportunites, bound capital	A wide sector: depends on application.	Growing	A wide sector: depends on application.	
Machinery & Tooling	**Prototyping in product development of machines**	1	Traditional technology	Depends on application.	A wide sector: depends on application.	A wide sector: depends on application. Various service providers	A wide sector: depends on application.	B to B	Cutting time.	A wide sector: depends on application.	Prototyping can have only limited impact	A wide sector: depends on application.	
Machinery & Tooling	**New innovative machines, and components, like low-cost robot arm, heat exchanges etc.**	1-2	Cases exist	Depends on application.	A wide sector: depends on application.	A wide sector: depends on application.	Supply chain difficult to discern due to various end uses	B to B	A wide sector: depends on application. Often higher performance.	A wide sector: depends on application.	Growing	A wide sector: depends on application.	http://www.3ders.org/articles/20150720-automatas-low-cost-3d-printed-eva-arm-hopes-to-bring-robotics-to-the-masses.html, http://www.makepartsfast.com/2015/02/7912/creating-multi-metal-custom-heat-exchangers-3d-printing/
Electronics & Electronic Devices	**Printing and embedding electronics for various**	2	Prototyping, research stage	Direct Write, FDM, SLA, multi3D systems	USA, e.g. Voxel8, University of Texas at El Paso,	E.g. Friedrich-Alexander-University Erlangen-	does not exist yet, emerging	B to B	Customised products	Conductive inks and filaments	Growing	E.g. clean energy through new	Espalin, D. et al., 3D-printing multifunctionality: structures with electronics. Int. J.

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
	devices. (e.g. batteries, 3D antennas, sensors)				Graphene 3D Lab., Optomec, nScrypt	Nuremberg, Germany, Bayerisches Lasercentrum GmbH, Germany, Manchester Metropolitan University, the UK,…						battery solutions.	Adv. Manuf Technol (214)72, p. 963-978. http://3dprintingindustry.com/2015/07/24/voxel8-ceo-jennifer-lewis-on-how-12m-in-funding-will-fuel-the-future-of-electronics-3d-printing/, http://www.graphene3dlab.com/s/technology.asp, http://www.wired.co.uk/news/archive/2015-08/10/graphene-3d-printed-super-batteries, Hoerber, J. et al., Approaches for additive manufacturing of 3D electronic applications. Procedia CIRP 17(214) p. 806 - 811, Nielse, B. et; Laser Sintering of Silver Ink for Generation of Embedded Electronic Circuits in Stereolithography Parts. Lasers in Manufacturing Conference 2015.
Electronics & Electronic Devices	**Cooling systems (e.g. Integration of cooling**	2	Research	SLM		Thales	does not exist yet, emerging	B to B	High-performance electronics	High conductive materials	Growing	New solutions.	Thales

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
	channels, high-performance heat sinks)												
Electronics & Electronic Devices	**Micro-electronics**	2	Prototyping	E.g. two photon polymerisation	Nanosccribe, Germany, AlpZhi, USA,…	Nanoscribe, Germany	does not exist yet, emerging	B to B	Microdevices	Photosensitive materials	Growing	New solutions.	http://www.alpzhi.com/#!, http://www.nanoscribe.de/en/technology/additive-manufacturing/
Consumer life style & fashion (inluding textiles and creative industries)	**Home decoration (incl. Lightning) (e.g. furniture, lightning, small statues, vases)**	1	Commercial	various technologies	e.g. Freedom of Creation (part of 3D systems) Neitherlands, LUXeXcel, Netherlands, .MGX (the design division of Materialise N.V.), Belgium	e.g. Freedom of Creation (part of 3D systems) Netherlands; LUXeXcel, Netherlands; Raybender, Denmark; KIORO design, Italy	e.g. various players with Materialize	b-to-c	Design freedom		Growing		http://www.freedomofcreation.com/collection/products
Consumer life style & fashion (inluding textiles and creative industries)	**Toys (e.g. figures, avatars, dolls, special building blocks)**	1	commecial	FDM	Insanitoy Inc. Mark Trageser (toy designer), US	e.g. Makielab (UK), Launzer (Finland), Lego, many others	Lego	b-to-c	series of one				https://mymakie.com/, https://www.launzer.com/ etc.

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Consumer life style & fashion (inluding textiles and creative industries)	**Textiles, cloths (e.g. shoes, bikinis, garments)**	1-2	Some experiments, e.g. haute couture garments since early 2010s. Gradually evolving. Fabric printers are developed.	SLS, FDM, PolyJet	US: Nervous System (a design studio), designers (e.g. Bradley Rothenberg), Footprint Footwear, the United Nude, Sols; US printer providers for textiles: 3D Systems Inc (Fabricate application). Israel also strong in design of clothes with 3D-printing elements.	NL: Iris van Herpen (fashion designer), ACryx (shoe brand); UK: Tamicare Ltd. (3D textile technology), BioKnit (shoe brand)	Luxexcel, NL (printer provider) optics, Philips, Adidas (GE), Grabher (AT)	b-to-c	Offering perfectly tailored clothing. Yet, haute couture is still hand-made intensive.	<u>current:</u> polymers, polymer composites, Abs, PLA, Flexible PLA, Polyamide, Multi-materials with different hardness shore value	Growing		Yap & Yeong: Additive manufacturing of fashion and jewellery products: a mini review, many others
Consumer life style & fashion (inluding textiles and creative industries)	**Smart textiles (e.g. sport textiles, protective textiles, smart helmets)**	2-3	Under research (as 3D-printed). Cases based on other technologies exist.	Material jetting, material extrution			IR: Ouro_botics (augmented tissue); SE: Chalmers University of Technology (3D-printing in cellulose); FI: Aalto University & VTT ,	b-to-c	better performance		Growing		

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
							AT: Grabher Group						
Consumer life style & fashion (inluding textiles and creative industries)	**Sport / Leisure (e.g. rackets, bikes, sporting shoes)**	1-2	E.g. sport shoes by Nike etc.		e.g. Nike (with Stratasys)	service providers		b-to-c	Improved performance				
Consumer life style & fashion (inluding textiles and creative industries)	**Music instruments (e.g. violins, guitars, panpipes, flutes)**	1	Many showcases. No commercialized products / no business cases / a few instruments sold (e.g. by Diegel)					b-to-c					Olaf Diegel etc.
Consumer life style & fashion (inluding textiles and creative industries)	**Jewellery (e.g. selective laser melting of precious metals like gold and silver, plastic jewellery, casted jewellery)**	1-2		SLM, EBM, SLA, Binder Jetting (ExOne M-Print, M-Flex), DLP (EnvisionTEC Perfactory), SLS	US: American Pearl Inc. (customers make their own design online, company produces 3D-printed wax mould); SG: Polychemy,	IT: Nemesi (online 3D-printing service for jewellery), KIORO design (design studio); NL(Eindhoven)/US: Shapeways (web based service), Dyvsign Delft; UK:	IR: Mcor Technologies (paper based 3D-printers for jewellery); Heimerle + Meule Group (refiner and processor	b-to-c	Customisation and personalization. Shorter supply chain. Quicker product development.		Growing	3D-printing is changing the economics of the jewellery design market drastically.	Yap & Yeong: Additive manufacturing of fashion and jewellery products: a mini review

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
						Cooksongold, Future Factories - Designer Lionel T Dean, Weston Beamor,FI: Kalevala koru	of precious metals), Swarovski						
Gas & Oil	**Oil & Gas**								Speed of continuing operations can be more important than the cost of the components				
Gas & Oil	**Prototyping (e.g. PIGs, valves, pump components)**	2	Printed PIG mock-ups accelerate production of actual PIGs		GE (oil and gas division)			B-to-B	Production efficiency, complex structures, customization		Prototyping can have only limited impact		Sikich – 3-D printing..
Gas & Oil	**Demanding parts (e.g. metal nozzles for gas turbines, electric submersile pump)**	2	piloting in 2014, expected production in 2015		GE (oil and gas division)	Siemens oil, gas and marine business		B-to-B	complex structures, better performance, maintenance support security, remote				Reuters – Oil industry

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
									environments				
Gas & Oil	**Parts for drilling**	2			Halliburton			B-to-B					
Energy	**Gas turbines: prototyping, repairing, direct manufacturing**	1	In commercial use	SLM, DED	Siemens, Mikro Systems, Inc. (US) subcontractor of Siemens	Siemens, Alstom (FR), Material Solutions Ltd (UK)	Siemens, Materials Solutions Limited (UK), Safran Group (FR), Alstom (FR)	B to B	Time saving, more energy-efficient solutions.	New metal powders.	Growing, rather narrow and specific supply chain acrros Europe	Material saving, more efficient energy production.	http://www.siemens.fi/pool/cc/events/elp14/esitykset/navrotsky.pdf, http://3dprintingindustry.com/2015/08/26/siemens-gas-turbines-to-get-a-boost-via-uk-metal-3d-printing-company/
Energy	**Solar panels and cells (e.g. optimized shape)**	2-3	Under research	Direct Write, Material Jetting,…	Several players starting the game around the world	Research groups e.g. in Holland	Does not exist	B to B	Saving in manufacturing costs. Efficiency, local manufacturing.	Printing on cheap materials.	Growing	Green energy.	L. van Dijk et al., Solar Energy Materials&Solar Cells 139(2015)1920 –26, http://www.energydigital.com/greentech/3793/Could-3D-Printing-Utterly-Change-Solar-Panel-Technology, http://www.theguardian.com/environment/blog/2013/feb/22/3d-printing-solar-energy-industry
Energy	**Wind power, hydro power, nucler power, fusion power, fuel cells,…**	2-3	Under research	Depends on the application	Different research groups around the world	E.g. an European project, led by Nuclear AMRC in the UK, going on in AM for nuclear components;	Does not exist	B to B	Depends on the application.	Depends on the application.		Green energy.	G. Scotti et al., Laser Additive Manufacturing of Stainless Steel Micro Fuel Cells, Journal of Power Sources 272 (2014) 356-361; M. Takagi et al, 3D-prined Pelton

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
						AT: Tegra Gmbh and Grabher-Group are producing textile electrodes for fuell cells							turbine: how to produce effective technology linked with global knowledge. Energy Procedia 61 (2014) 1593 – 1596; V. Queral, 3D-printed fusion component concepts and validation for the UST.2 stellarator, Journal of Physics: Conference Series 591 (2015) 012015; http://www.materialstoday.com/metal-industry/news/uk-nuclear-industry-investigates-pm-techniques/
Construction	**Affodable houses (based on automatisa-tion, redundancy of formworks)**	2	under research / demonstration	Exstrution type printing	WinSun (China), RMIT Institute of Technology (Australia), University of Southern California, Zhuoda Group (China), entrepreneur Lewis Yakich (3D-printed homes in Philippines)	Fimatec (Finland), DUS Architects (NL); Dshape - Monolite Ltd (UK)	IT: WASP (World Advanced Saving Project) creation of the world's largest Delta 3D-printer. AT: Lukas Lang Building Technologies and REHAU AG		Costs		Growing, large supply chains are affected across Europe		Perrot et. al. (France)

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Construction	**On-the-spot emergency shelters**	2	under research / demonstration	Exstrution type printing	WinSun (China)	University of Nantes (France) in conjunction with CAPACITES SAS			Time				University of Nantes
Construction	**Architectural flexibility (e.g. pillars, shape of house)**	2	under research / demonstration	Exstrution type printing	DUS architects (3D-print Canal House), Neitherlands				Estethics (time and cost)				
Construction	**Printed bridges and other similar applications**	2	under research / demonstration	DED type printing									Skanska (t&), Nottingham/Lougborough

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Military	**Spare parts (mobile factories, fighters, printers on ships,..)**	1-2	Testing, first cases.		US Army, Chinese Army,	British Army	E.g. BAE Systems and RAF	B to B	Logistics. Quality and speed of maintenance. Money savings.	Depends on the application	Growing	The technology developed can be used also in civilian applications.	http://www.3ders.org/articles/20140105-uk-tornado-fighter-jets-fly-with-3d-printed-parts-for-the-first-time.html, http://www.wired.co.uk/news/archive/2015-02/09/mod-future-of-army-technology, http://www.usni.org/magazines/proceedings/2013-04/print-me-cruiser, http://uk.businessinsider.com/afp-how-3d-printing-could-revolutionise-war-and-foreign-policy-2015-1?r=US#ixzz3eXum1HW5
Military	**Temporary housing**	2	Testing		US Army	Does not exist	Does not exist		Shelters in remote areas	Concrete, etc.	Growing	Also for humanitarian operations and disaster relief.	Horowitz. M.C. (2014) Coming next in military tech. Bulletin of the atomic Scientists. Vol. 70(1), pp. 54-62.
Military	**Field hospitals**	2-3	Testing		US Army	Does not exist	Does not exist.		Fast treatment on spot of demand (printing implants, healing burn	Depends on the application	Growing	Also for civilians.	http://www.3dprinterworld.com/article/wake-forest-3d-prints-skin-cells-burn-wounds, http://qz.com/145237/3-ways-3-d-printing-could-revolutionize-healthcare-2/

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
									wounds,...)				
Military	**Personalized dashboard and controls**	2	under research / demonstration				Have not been recognised						
Military	**special equipments**	2	under research / demonstration				Have not been recognised						http://www.wired.com/2013/04/3d-printed-navy/
Military	**spare parts**	2	under research / demonstration				Have not been recognised						http://3dprintingindustry.com/2015/07/08/3d-printing-sought-to-improve-spare-parts-manufacturing-for-marine-industry/, http://gcaptain.com/printing-change-world/#.VdXSke8w9aQ
Military	**Engine parts**	3	under research / demonstration				Have not been recognised						
Military	**customized cabins**	2	under research / demonstration				Have not been recognised						
Food industry	**Personalized food - shape (chocolate printer)**	1	First commercial applications available (e.g. chocolate printer etc.)	Mainly exstrution type printing	3D systems	e.g. Biozoon	Have not been recognised		customization and personalization				many sources

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Food industry	**Food for remote locations (e.g. food in space, food in battlefield)**	3	under research	Mainly exstrution type printing	NASA, US army		Have not been recognised		remote operations				http://www.sciencedaily.com/releases/2015/07/150713144118.htm
Food industry	**Personalized food - incredients, structure, flavour (e.g. personalized diet, improved flavour by improved stucture)**	2	demonstration and first commercial use	Mainly exstrution type printing	3D Systems (US) produces food printers	e.g. Biozoon, Print2Taste Bocusini (Germany), TNO (Research) Neitherlands, the Foodini by Natural Machines (ES), Nestle (CH) , the Choc Creator by Choc Edge (UK), MELT icepops (NL), The Magic Candy Factory (DE)	3D Ventures (UK);		personalization, mass customization		Growing, has an impact also on many small firms		http://3dprintingindustry.com/2015/04/24/print2taste-emerges-with-the-bocusini-food-3d-printer/, http://www.thewire.com/technology/2014/05/3d-printed-food-actually-looks-and-tastes-pretty-delicious/371863/
Entertainment Industry	**Movies**	1	Used for creating special effects in movies, costume design, etc. Animations. Broadly in use.		e.g.: Legacy Effects (Hollywood special effects studio), US	UK (animation)		b-to-b	Lower costs and faster processes (e.g. in prototyping).				TNO projects
Entertainment Industry	**Games - 3D CAD and 3D file**					Materialise, Altair, etc.							https://i.materialise.com/

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
	manipulation software												
Optics	**Led lights**	2	Used in LED lighting industry mainly	stereolithography (SLA), multi-jet modeling (MJM) and PolyJet (from Stratasys, Eden Prairie, Minn.)	Formlabs, a 3D-printer company in Somerville, Mass., developed a unique way to polish their 3D-printed lenses.	LUXeXcel, Netherlands	Philips, OSRAM in cooperation with LuXeXcel	b-to-b		Poly(methyl methacrylate) (PMMA) a transparent thermoplastic, Optical liquid silicone rubber (LSR)	extend to consumer market spectaculars, 3D-printed "light pipes" that enable construction of unique display surfaces, novel illumination techniques, custom optical sensors and embedded optoelectronic components.		
Optics	**fiber optic cables**												http://3dprintingindustry.com/2015/08/20/breakthrough-glass-3d-printing-platform-unveiled-by-neri-oxman-mit/?utm_source=3D+Printing+Industry+Update&utm_medium=email&utm_campaign=cfd636340c-

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
													RSS_EMAIL_CAMPAIGN&utm_term=0_695d5c73dc-cfd636340c-64521293
Optics	**lightning**												

Source: IDEA Consult, AIT and VTT, 2015

4/ Case studies

4.1 Introduction to the case studies

4.1.1 Context: re-positioning the case studies in the project

The first sections of the report focused on the identification of the most important future applications in 3D-Printing[337], considering the applications at post-prototyping level (> TRL5) with a potential market deployment within the 3 to 5 years. The identification of these key applications relied on a wide set of mutually-reinforcing analyses such as patent data analysis, bibliometric analysis, FP-funded projects' analysis, or literature review. A large set of 65 key applications were identified and ranked according to their technological maturity and market potential. This first part of the report led to the selection of the top-ten most promising 3DP-applications. This section depicts the process followed to select the cases in order to get from the long-list of 65 applications to the short list of 10. The selection process consisted in three main blocks:

1. Profiling of the regions in terms of several criteria, including specialization;
2. Selecting and positioning regions in terms of their regional profile and their link to one of the 10 applications;
3. Selecting the ten cases, a case being a combination of an application are and a set of pre-identified regions to remain indicative[338].

The case study selection was based on the positioning of EU-regions based on their expected capabilities, needs and ambitions in 3DP (based on the analysis of their regional specialization profiles and smart specialization strategies). As a result, 10 application areas were selected to be further researched during Task 2. By the research consortium. These application areas were selected in close collaboration with the European Commission and are presented in Section 4.1.2.3. For each application, the case studies to be implemented in two steps to allow:

- Re-constructing the value chain(s) segment by segment by identifying key players (companies, research and technology organisations, clusters etc.) and their activities;
- Identifying missing competencies in the regions considered and opportunities for joint activities between them.

After the selection of the 10 application-driven value chains to be further investigated, each case study was conducted by using a combination of desk research and semi-structured interviews. The case study process was framed by the use of a case study protocol depicting every aspect of the process, topics to be discussed, analysis and reporting modalities. The value chain analyses were completed by an identification of barriers to the uptake and deployment of Additive Manufacturing together with related policy implications.

4.1.2 Methodology to profile, select and position the regions

4.1.2.1 Selection and positioning the regions

Parallel to the identification of the application domains, we started an exercise to describe and select key regions to be combined with sector-application areas in order to constitute cases to be studied in depth. Our team proceeded to a step-by-step approach to identify the main economic domains & niches in approximately 70 regions, in order to link them to the defined application domains. First, a long-list of regions was established by the team. These regions were listed in function of the on-line information available on their socio-economic structure. Therefore, a list of 70 regions covering the whole EU28 was put together by the consortium. We kept the right geographical coverage, and also paid attention to the balance between lead and less advanced regions in specific countries. This with the aim to identify both regions with supply capacities and demand opportunities for 3D applications.

In order to step further, the team gathered relevant information available on the web to categorise each of the regions already listed. The team identified what position the region held in terms of 3D-Printing positioning (existing capacity / demand potential / combination of both) and thematic structure. Then, further information was collected in order to inform the analytical table with the five top economic sectors or socio-technical areas for each region available.

337 As agreed before we consider 'Additive Manufacturing' (AM) and '3D-Printing' (3DP) as synonims.

338 The value chain analysis for each of the application case was indeed to lead to a more accurate identification of regional capabilities for each of the selected applications.

A grid was used to guide the information collection process. This grid established four main categories of information to be gathered for each region:

1. **Regional Structure – First Scan**

This section was providing information on the regional structure: dominating sectors and industrial structure were among the main points looked at together with existing knowledge capacity. This provided a first overview on the regional structure and provided the team with first possibilities to acknowledge current or potential sector-application areas.

2. **3DP Capacity – First Scan**

The data collection for this section was dedicated to the 3D-Printing capacities of each region. It was to be discovered for each region whether it held a position of Supplier, (potential) Demander, and/or both combined. Of course, all regions have a potential of demand by nature. But the purpose of this section was mainly to spot regions with existing capacity, whether early or late on the TRL scale.

3. **Strategy – Development targets**

Another aspect lied in regional economic development strategies and, since more recently, Smart Specialisation Strategies. The key development areas selected by a region can inform about possible future developments but also existing strengths of the region. Cross-checking the Specialisation Areas and priorities in relevant S3 allowed relating demand and supply potential for some of the regions with clear and well-defined priorities. Beyond the Vanguard regions for instance, one of the regions mentioned 3DP as part of the potential development sectors for its software industry.

4. **Regional Specialisation – Current specialisation patterns**

Mainly based on data from the Cluster Observatory completed by RIM-Plus reports on advanced manufacturing, this section was at the core of the search. We listed for each region the top-five sectors in terms of 1) Employment and 2) Regional specialisation. Additional information on advanced manufacturing was here added. 3DP clusters were also to be listed here -although not many were listed- as well as information on possible sector-application areas with potential for 3DP. For instance, projects relating to advanced manufacturing and sometimes 3DP could be identified.

Some balance in terms of the geographical location of the regions was sought as to foster an optimal coverage of the EU-28 area. In order to counter-balance for the weight of the Vanguard-regions (mainly Western-European), the team paid particular attention to Eastern-European regions. The information was collected from a number of sources. After a first round of 5 pilot regions, the team decided to re-shuffle the priority order of the available sources as to make use of three primary sources completed by additional sources. The table below (Table 24) highlights which sources were used in which order.

Table 24: Information Sourcing - Overview

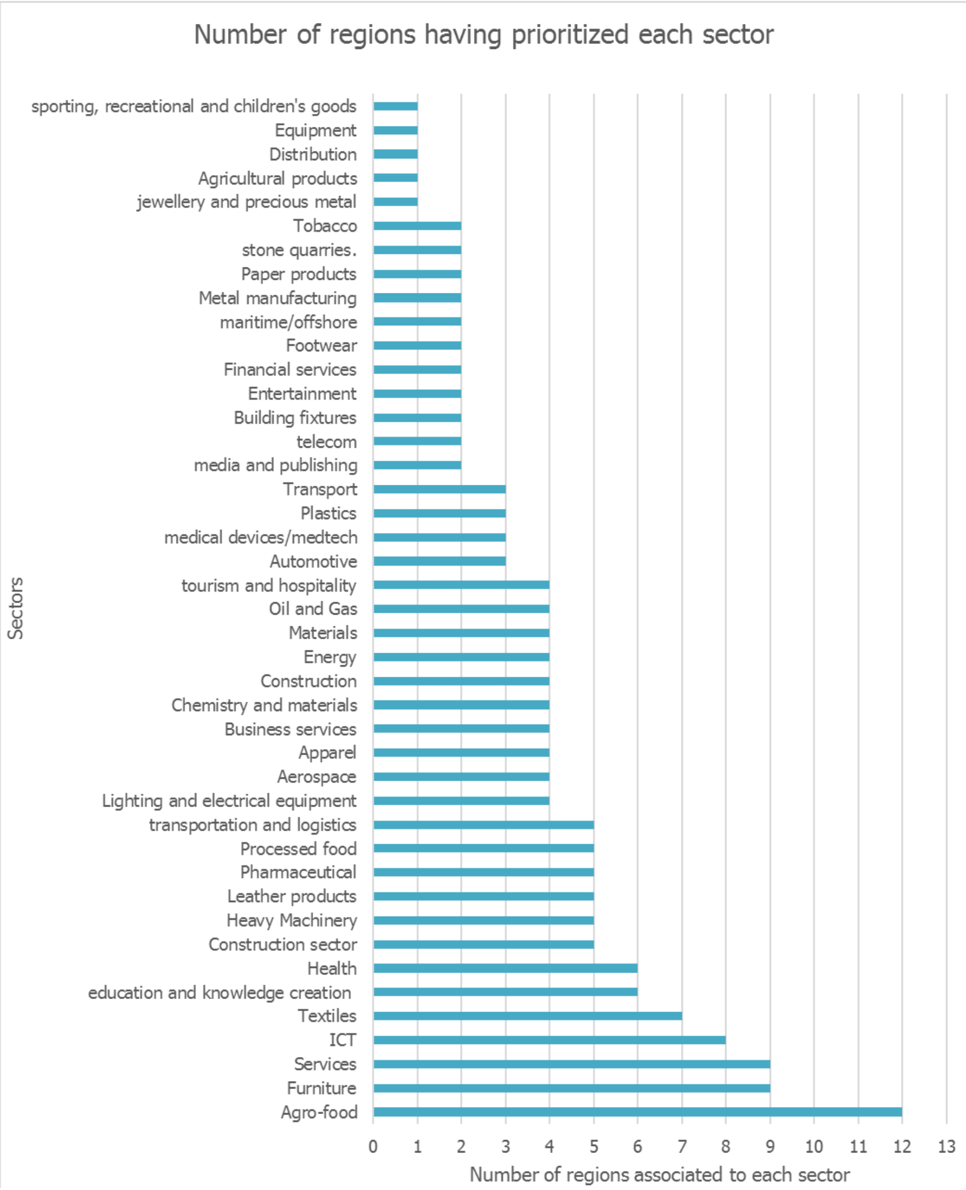
Name	Link
Primary Sources	
The Smart Specialisation Platform or the "Eye@S³ Tool" of the IPTS	*Link:* *http://s3platform.jrc.ec.europa.eu/home* *and* *http://s3platform.jrc.ec.europa.eu/map*
Regional Innovation Monitor Plus	*Link:* *https://ec.europa.eu/growth/tools-databases/regional-innovation-monitor/*
Reports and indicators from the Cluster Observatory	*Link:* *http://www.clusterobservatory.eu*
Secondary Sources	
ERAWATCH	*Link:* *http://erawatch.jrc.ec.europa.eu/erawatch/opencms/information/reports/reg_level/?country=-1*
EUROSTAT data	*Link:* *http://ec.europa.eu/eurostat/statistics-explained/index.php/Structural_business_statistics_at_regional_level*
Web-based sources (used in a very occasional fashion):	▸ Official websites from the **regional governments** under the scope ▸ **EU Service Innovation Scoreboard** ◆ Link: http://ec.europa.eu/growth/tools-databases/esic/scoreboard/esis-database/index_en.htm ▸ **OECD** reports on Regional Innovation Policy and the OECD Innovation Policy Platform ▸ **National** Statistics Offices ▸ **Intermediary** sources (EU or sub-EU platforms as well as federations and similar intermediates)

Source: IDEA Consult, 2015

As a result, a classification table highlighting the dominant sectors for each region as well as the other items mentioned above[339] was produced. A synthesis was operated through pivot tables in order to cluster the regions in function of the sectors they prioritised in first to fifth position. When brought altogether, the sectors that appeared to be of main importance for the EU regions under the scope were ranked in function of the number of regions to which they were associated. These sectors and related ranking are the following (see):

[339] 1. Regional Structure – First Scan; 2. 3DP Capacity – First Scan; 3. Strategy – Development targets; and 4. Regional Specialisation – Current specialisation patterns

Figure 30: Regional prioritisation - Sectoral overview



Source: IDEA Consult, 2015

The sectors were prioritised in function of the number of regions they were associated to. A first clustering of the regions per sector was conducted by the team. In addition to the sectoral clustering, a colour code was given to "areas" bringing together sectors with connections and/or similarities. In total, 40 sectors were listed and associated to one or more region(s).

1. **Agro-food**: Groningen, Helsinki-Uusimaa region, Lithuania (instead of only Aukštaitija and Samogitia for which no public information seems to be available), Lubelskie, Malopolskie, Midi-Pyrénées, North-Vest, Region of Thessalia, Severoiztochen, Southern and Eastern Ireland, Southern Denmark Region, Yugoiztochen
2. **Processed food**: Burgenland, Kujawsko-Pomorskie, Lower Austria, Podlaskie, Voivodship, Region of Thessalia
3. **Tobacco**: Groningen, Region of Thessalia
4. **Agricultural products**: Region of Thessalia
5. **Textiles**: "Croatia proper", Lubelskie, Malopolskie, Marche, North east, North-Vest, Yugoiztochen,
6. **Leather products**: Centre, "Croatia proper", Lisbon, Rhône-Alpes, Severoiztochen
7. **Apparel**: Centre, "Croatia proper", Kujawsko-Pomorskie, Yugoiztochen
8. **Footwear**: Centre, Stredni Morava
9. **Sporting, recreational and children's goods**: Stredni Morava
10. **Tourism and hospitality**: Border, Midland and Western, Helsinki-Uusimaa region, North east, Severoiztochen
11. **Services**: Utrecht, Dolnoslaskie, Helsinki-Uusimaa region, Ile-de-France, Lancashire / North West England, Lithuania (instead of only Aukštaitija and Samogitia for which no public information seems to be available), Marche, Midi-Pyrénées, Southern and Eastern Ireland
12. **ICT**: Utrecht, Border, Midland and Western, Dolnoslaskie, Helsinki-Uusimaa region, North east, North-Vest, Prague/Praha, Severoiztochen
13. **Business services**: Utrecht, Corse, Lancashire / North West England, Lisbon
14. **Media and publishing**: Lisbon, Prague/Praha
15. **Telecom**: Lithuania (instead of only Aukštaitija and Samogitia for which no public information seems to be available), Prague/Praha
16. **Entertainment**: Corse, Ile-de-France
17. **Financial services**: Utrecht, Corse
18. **Health**: Utrecht, Helsinki-Uusimaa region, Midi-Pyrénées, North east, Northern Ireland, Southern Denmark Region
19. **Pharmaceutical**: Border, Midland and Western, Central Hungary, Midi-Pyrénées, Prague/Praha, Rhône-Alpes
20. **Medical devices/medtech**: Border, Midland and Western, Rhône-Alpes, Southern and Eastern Ireland
21. **Construction sector**: Bratislava Region, Corse, Southern and Eastern Ireland
22. **Construction**: Dolnoslaskie, Lancashire / North West England, Region of Thessalia, Southern Denmark Region
23. **Building fixtures**: Burgenland, Lubelskie
24. **Stone quarries**: Border, Midland and Western, Malopolskie
25. **Heavy Machinery**: Central Hungary, Marche, Podkarpackie, Podlaskie Voivodship, Yugoiztochen
26. **Transport**: Dolnoslaskie, North-Vest, Southern and Eastern Ireland
27. **Transportation and logistics**: Central Hungary, Ile-de-France, Lisbon, Lithuania (instead of only Aukštaitija and Samogitia for which no public information seems to be available), Southern Denmark Region
28. **Aerospace**: Ile-de-France, Lancashire / North West England, Midi-Pyrénées, Podkarpackie
29. **Automotive**: Dolnoslaskie, Lancashire / North West England, Podkarpackie
30. **Maritime/offshore**: Podlaskie Voivodship, Yugoiztochen
31. **Oil and Gas**: Central Hungary, Centre, Groningen, Lower Austria
32. **Energy**: Lithuania (instead of only Aukštaitija and Samogitia for which no public information seems to be available), Lubelskie, Southern Denmark Region, Stredni, Morava
33. **Chemistry and materials**: Bratislava Region, Malopolskie, Rhône-Alpes, Severoiztochen
34. **Materials**: Bratislava Region, Malopolskie, Northern Ireland, Stredni Morava
35. **Plastics**: Bratislava Region, Kujawsko-Pomorskie, Podkarpackie
36. **Metal manufacturing**: Lower Austria, Marche
37. **Paper products**: Kujawsko-Pomorskie, Marche
38. **Jewellery and precious metal**: Groningen
39. **Distribution**: Lisbon
40. **Equipment**: Lower Austria

4.1.2.2 Selection of the ten cases: the thematic perspective

Goals: After completing the SAM and the regional selection grid, the workshop focused on matching the two in order to:

1. Select the most relevant 3DP applications to consider for the case studies;
2. Allocate regions to these application areas;
3. Eventually, validate the resulting combinations as cases to be further investigated during the next steps of the project.
4. Establish a long list of cases from which ten case-studies will be finally selected.

Approach: a one-day workshop with two main sessions was organised in the form of a protocolled focus group. Both main sessions gathered the consortium partners (including CECIMO) as well as a representative from the Institute of Prospective and Technological Studies (IPTS). The process followed the structure presented below:

Morning session – Prioritisation and selection of the key applications

1. Introduction by the team leader
    a. Attendance, project status, debrief from previous client telco and objectives of the session
2. Presentation of the SAM by consortium partners
    a. Process followed
    b. Results
    c. Issues and challenges
3. Tour de table – first comments from the participants on the SAM
4. Rows and columns at stake: comments on specific items
    a. Structure of the grid
    b. The sectoral divide
    c. The applications
    d. Content
    e. Structure of the grid
    f. The sectoral divide
    g. The applications
    h. Content
5. Listing of the points of attention and Validation of the final SAM
6. Wrap-up of the session by the team leader

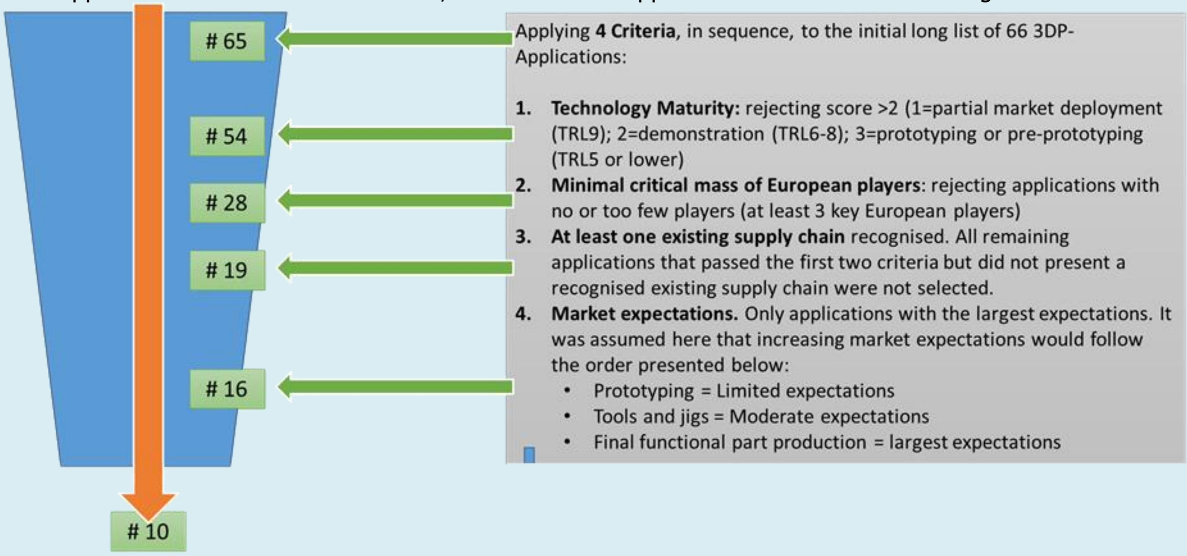
After the introduction of the session and the presentation of the SAM by team members, a discussion followed on the scope of the sector-application areas, resulting in the validation of the structure and content of the grid with few amendments. It was decided to add additional examples to the SAM in order to better illustrate the areas under the scope.

The team performed a prioritisation exercise under the guidance of the project leader: for each sector, one or more relevant applications presenting a maximum potential were selected and retained in view of the second workshop session.

Starting from the long list of 65 3DP applications identified under the previous tasks (see results under task 1.6, we ranked and prioritised the applications according to the following key criteria:

1. Technology Maturity was used as first selection criterion. Following the rationale of the study, which aims at considering close-to-market application areas in the first place, the team identified the applications with a maturity level higher than 2 in order to filter them and only keep application areas with a maturity level equivalent or lower than 2.
2. A second criterion was the presence of a minimal critical mass of European players (suppliers) recognised. All applications with no or too few players (at least 3 key European players) were left aside.
3. The presence of at least one existing supply chain recognised was made third criterion for the selection of applications. All remaining applications that passed the first two criteria but did not present a recognised existing supply chain were not selected.
4. Finally, market expectations were used as final filter. Only applications with the largest expectations would be selected. It was assumed here that increasing market expectations would follow the order presented below:
    a. Prototyping = Limited expectations
    b. Tools and jigs = Moderate expectations
    c. Final functional part production = largest expectations

Each criterion was used as a filter: every application area that would not match the expectations of a filter would be dropped from the selection. Therefore, the selection of applications followed four "filtering" rounds:



Using these criteria, <u>we prioritised the applications and selected 16 key 3DP-applications for further research</u>. The list is shown below in Table 25.

Afternoon Session – Allocation of the regions to the 16 selected applications

1. Introduction by the team leader
    a. Attendance and objectives of the session
2. Presentation of the regional grid by the team leader
    b. Process followed
    c. Results
    d. Issues and challenges
2. Tour de table – Comments on the grid and relevant adjustments/complements
3. Discussion on the regions to be selected – ROUND 1
    a. Open Question: are there regions that are missing in the grid and should be added to the list?
    b. Open question: is there information in the grid that is missing or incorrect?
    c. Scoping question: what are the main clusters we should prioritise (aerospace? Etc.)?
4. Discussion on the regions to be selected – ROUND 2
    a. Selection question: which are the less relevant regions we could leave aside?
    b. What are the regions corresponding to each of the main clusters (10 clusters in total)
    c. Validation of the 25 candidate regions (+ 5 optional regions) for each of the 10 clusters (to become case studies)
5. Conclusion of the workshop and presentation of the uptake of its results and next steps

The second session was aimed at allocating relevant regions to the selected applications, based on the preparatory work presented in TASK 1.6 (see section 4.1.2.1). The preparatory work produced an overview of more than 70 regions, each positioned according to its specialisation structure (industrial specialisation) and regional strategy. Both these aspects were analysed at regional level and each region was positioned against its 3DP-capabilities and/or potential absorptive capacity.

For instance, a region with an industrial texture skewed towards the automotive sector, with a regional ambition in 'Advanced Manufacturing' in its innovation strategy, and with the presence of a cluster organisation with some activities in Additive Manufacturing (e.g. Lower Austria) may have at least the capacity and the interest to absorb and integrate new 3DP applications related to the automotive sector (if not the potential to develop them itself). The same reasoning was followed for all 70 regions.

However, it should be borne in mind that this allocation is merely based on public and codified sources, leaving room to some further evolution when the case-studies will be actually launched. The criteria used for the allocation were:

1. Relevant industrial activity in the field (or in a related field);
2. Critical mass, assessed through the presence of key (significant) industrial players in the region[340] (either as supplier of 3DP applications (technology developer) or as potential lead-user) ;
3. A potential leading role in terms of the segments of the value chain missing (upward/downward segments).

The results of the workshop sessions included the following:

- A completed and refined SAM;
- A prioritised list of applications to be considered as field cases in the form of a long-list of applications;
- A grid integrating the long-list of 16 applications and the regions from the regional grid according to the criteria described in the boxes above.

The resulting long-list of 16 combinations between application areas and regions is described below (see Table 25). By the next step of the project, the team will study in-depth 10 cases out of the list of 16 short-listed region-application combinations.

340 Notice here that although the team used indicators such as employment and specialization indices for each of the regions under the scope, the presence of key (leading) players might sometimes not impact the specialization pattern of a region. Therefore, the sectoral specialization of a region might not translate its real 3DP strength and/or position along relevant value chain(s).

Table 25: Overview of the selected key Sector-Application areas and regions (long-list of cases)

	Technology	Geographical Concentration		European Supply Chain	Potential	Regions
	Maturity	*Global key players*	*Key European players*	*Network*	*Market expectation*	
Structural parts for airplanes, especially engines (e.g. turbine blades, fuel nozzles)	1-2	General Electric (GE Aviation / Morris Technologies), SNECMA, Hamilton Sundstrand, Boeing, Honeywell International Inc., Lockheed Martin,… CFM International (joint venture of GE & Snecma), Amaero (Australia)	AvioAero by GE Aviation (Turin/Milan), Rolls Royce, BAE Systems, Snecma (FR) …	Airbus and its suppliers, Graphite Additive Manufacturing (UK), Avio (Italy), Arcam (Sweden)	Growing	Aragon, Lombardy, South Holland, Upper Austria, Wallonia, Midi-Pyrénées, Piemonte, Campania, Ile-de-France, Lancashire, North West England, East Midlands, Podkarpackie, Hampshire
Component repairing, based on directed energy deposition and hybrid technologies (e.g. aircraft engine compressor components, blisks (intergrally bladed rotors), airfoils)	1-2	Sciaky, Optomec, Lockheed Martin, …	Trumpf-Sisma, Fraunhofer ILT, Hermle (Germany), Wojskowe Zakłady Lotnicze Nr 2 (Polish aircraft repair company), UK Space Agency, Airbus…	E.g. Rolls-Royce Deutschland, Fraunhofer ILT; Zortrax, Poland (3D-printer manufacturer)	Growing	Aragon, Lombardy, South Holland, Upper Austria, Wallonia, Midi-Pyrénées, Piemonte, Campania, Ile-de-France, Lancashire, North West England, East Midlands, Podkarpackie, Hampshire
Personalized car interiors (e.g. dashboard) and exteriors (e.g. wing mirrors and other non-	1-2	e.g. BMW. Several Chinese companies (e.g. Shanghai Dragon Automot Technol Co Ltd)	BMW, Ai Design (customized car manufacturer); Italy: Ferrari, Lamborghini, Agusta, Ducati; Mercedes,	e.g. BMW using stratasys technology, EOS, Additive manuf. Services: CRP Group, Skorpion, Energy Group and Proto Service	Growing	Baden-Wurtemberg, Aragon, Cataluna, Emilia-Romagna, Lombardy, Norte, Saxony, Slovakia (Bratislava), Bavaria, Piemonte, Thuringia, Dolnoslaskie, Podkarpackie, North/West England,

	Technology	Geographical Concentration		European Supply Chain	Potential	Regions
	Maturity	*Global key players*	*Key European players*	*Network*	*Market expectation*	
sturctural components)		have wide patent portfolio				Castilla, Gothenburg, Västergötland, Nord Pas de Calais, IdF(?), Moravia (CZ), Yugozapaden (BU), Argeş County (RO),
Demanding components (e.g. gear box, powertrain parts, water pump wheel)	1-3	e.g. BMW	BMW, Germany; Prodrive (UK); Fiat Chrysler Automobiles (FCA);	Michelin joint venture with Fives (metallic AM), France	Growing, large and broad supply chain across Europe	Baden-Wurtemberg, Aragon, Cataluna, Emilia-Romagna, Lombardy, Norte, Saxony, Slovakia (Bratislava), Bavaria, Piemonte, Thuringia, Dolnoslaskie, Podkarpackie, North/West England, Castilla, Gothenburg, Västergötland, Nord Pas de Calais, IdF(?), Moravia (CZ), Yugozapaden (BU), Argeş County (RO),
Inert implants, hard implants i.e. bone replacement (e.g. acetabular implants, skull implants, sternum implants)	1-2	e.g. Oxford Performance Materials (US)	e.g. Symbios (UK), joimax (German), Layerwise (part of 3D Systems), Belgium, Nanotec Marin GmbH (Germany), Stanmore Implants Worldwide, 3T RPD Ltd, Implantcast GmbH, 3Dceram	WASP (Italy); Materialise (Belgium); Arcam AB (Sweden),	Growing, very innovate industry is emerging	Flanders, Asturias, Lombardy, Emilia-Romagna, Nord pas de Calais, Aragon, Baden-Württemberg, South NL, Tampere, Wallonia, Cataluna, Thuringia, Midi-Pyrénées, Rhône-Alpes, Northern Ireland, South Denmark, Helsinki, Podlaskie
Tools, instruments & parts for medical devices (i.e. tools and jigs for surgery, i.e. Kelly hemostat, needle driver, tissue forceps,	1-2	Many US hearing aid manufacturers e.g. GN ReSound , 3D Systems, Medical Modeling,	Siemens, Lima Corporate (Italy), GN ReSound (Denmark), EnvisionTEC Germary, DSM	LayerWise, Belgium (advanced direct metal 3D-printing and manufacturing services);Materialise (Belgium); EOS, Germany; Ruetschi Technology AG (Switzerland), Concept Laser GmbH (Germany), EnvisionTEC with GN ReSound	Growing	Flanders, Asturias, Lombardy, Emilia-Romagna, Nord pas de Calais, Aragon, Baden-Württemberg, South NL, Tampere, Wallonia, Cataluna, Thuringia, Midi-Pyrénées, Rhône-Alpes, Northern Ireland, South Denmark, Helsinki, Podlaskie

	Technology	Geographical Concentration		European Supply Chain	Potential	Regions
	Maturity	*Global key players*	*Key European players*	*Network*	*Market expectation*	
retractor, scalpel handle and Metzenbaum scissors) (eventually also consider exoskeletons)						
Dental (e.g. crowns, braces and dentures), also dental devices	1-2	e.g. Align Technologies Inc (Invisalign Dental braces), DENTCA (USA), Stratasys (Israel/USA)	3DMedicalPrint, Austria; SLM Solutions Germany; EOS Germany; Concepts Laser Germany; Planmeca Group, Finland, Mat Dent NV, Implant & 3D Planning Ctr, Skyscan NV	Roboze, Bari Italy (High precision printer manufacturer)	Growing, strong impacts	Flanders, Asturias, Lombardy, Emilia-Romagna, Nord pas de Calais, Aragon, Baden-Württemberg, South NL, Tampere, Wallonia, Cataluna, Thuringia, Midi-Pyrénées, Rhône-Alpes, Northern Ireland, South Denmark, Helsinki, Podlaskie
Metallic mould inserts for injection moulding and die casting	1	Marketed strongly by Stratasys.	Major companies in different end-user sectors, e.g. automotive, consumer, aerospace, medical. Volvo Trucks (Lyon FR)	Some supplies exist, like Fado in Poland; Additive Industries (NL); Mcor, Ireland; EOS, Germany, InvisionTEC, Germany	Growing, strong impacts on the value chain across Europe	Baden-Württemberg, Cataluna, Emilia-Romagna, Flanders, Lombardy, Nord pas de Calais, South Holland, South NL, Tampere, Thuringia, Upper Austria, Wallonia, Norte, Orebro Lan, Marche, Lower Austria, Copenhagen, Central Hungary, Podkarpackie, Podlaskie (PO), Yugoiztochen (BU), Västergötland (Gothenburg Region), South East Romania, Malopolskie, Central Greece, Silesia

	Technology	Geographical Concentration		European Supply Chain	Potential	Regions
	Maturity	*Global key players*	*Key European players*	*Network*	*Market expectation*	
Sand moulds and cores for foundries when individual castings are needed. Plastics patterns for sand casting.	1	For sand moulds and cores: ExOne, headquarters in the USA. Stratasys active in marketing pattern making. Several players in US	For sand moulds and cores Voxeljet in Germany; Sand Made, Poland, Newbyfoundries, UK, 3Dealise Ltd UK	ExOne (The development and production facility in Augsburg, Germany)and Voxeljet supply services. Also other suppliers. Foundries. Several application industries.	Growing, large and diverse supply chain acoss Europe	Baden-Württemberg, Cataluna, Emilia-Romagna, Flanders, Lombardy, Nord pas de Calais, South Holland, South NL, Tampere, Thuringia, Upper Austria, Wallonia, Norte, Orebro Lan, Marche, Lower Austria, Copenhagen, Central Hungary, Podkarpackie, Podlaskie (PO), Yugoiztochen (BU), Västergötland (Gothenburg Region), South East Romania, Malopolskie, Central Greece, Silesia
Spare parts for machines (e.g. gears, housings, buttons, fasteners)	1-2	A wide sector: depends on application.	A wide sector: depends on application. Maersk, DK (Fabricate Spare Parts on Ships), online suppliers like Shapeways, iMaterialize and other AM service providers	A wide sector: depends on application.	Growing	Baden-Württemberg, Cataluna, Emilia-Romagna, Flanders, Lombardy, Nord pas de Calais, South Holland, South NL, Tampere, Thuringia, Upper Austria, Wallonia, Norte, Orebro Lan, Marche, Lower Austria, Copenhagen, Central Hungary, Podkarpackie, Podlaskie (PO), Yugoiztochen (BU), Västergötland (Gothenburg Region), South East Romania, Malopolskie, Central Greece, Silesia

	Technology	Geographical Concentration		European Supply Chain	Potential	Regions
	Maturity	*Global key players*	*Key European players*	*Network*	*Market expectation*	
Home decoration (incl. Lightning) (e.g. furniture, lightning, small statues, vases)	1	e.g. Freedom of Creation (part of 3D systems) Neitherlands, LUXeXcel, Netherlands, .MGX (the design division of Materialise N.V.), Belgium	e.g. Freedom of Creation (part of 3D systems) Netherlands; LUXeXcel, Netherlands; Raybender, Denmark; KIORO design, Italy	e.g. various players with Materialize	Growing	Galicia, Cataluna, South NL, Nord pas de Calais, Lombardy, Flanders, Ile-de-France
Textiles, cloths (e.g. shoes, bikinis, garments)	1-2	US: Nervous System (a design studio), designers (e.g. Bradley Rothenberg), Footprint Footwear, the United Nude, Sols; US printer providers for textiles: 3D Systems Inc (Fabricate application). Israel also strong in design of clothes with 3D-printing elements.	NL: Iris van Herpen (fashion designer), ACryx (shoe brand); UK: Tamicare Ltd. (3D textile technology), BioKnit (shoe brand)	Luxexcel, NL (printer provider) optics, Philips, Adidas (GE), Grabher (AT)	Growing	Galicia, Cataluna, South NL, Nord pas de Calais, Lombardy, Flanders, Ile-de-France
Jewellery (e.g. selective laser melting of precious metals like gold and silver, plastic jewellery, casted jewellery)	1-2	US: American Pearl Inc. (customers make their own design online, company produces 3D-printed wax mould); SG: Polychemy,	IT: Nemesi (online 3D-printing service for jewellery), KIORO design (design studio); NL(Eindhoven)/US: Shapeways (web based service), Dyvsign Delft; UK:	IR: Mcor Technologies (paper based 3D-printers for jewellery); Heimerle + Meule Group (refiner and processor of precious metals), Swarovski	Growing	Galicia, Cataluna, South NL, Nord pas de Calais, Lombardy, Flanders, Ile-de-France

	Technology	Geographical Concentration		European Supply Chain	Potential	Regions
	Maturity	*Global key players*	*Key European players*	*Network*	*Market expectation*	
			Cooksongold, Future Factories - Designer Lionel T Dean, Weston Beamor,FI: Kalevala koru			
Gas turbines: prototyping, repairing, direct manufactu-ring	1	Siemens, Mikro Systems, Inc. (US) subcontractor of Siemens	Siemens, Alstom (FR), Material Solutions Ltd (UK)	Siemens, Materials Solutions Limited (UK), Safran Group (FR), Alstom (FR)	Growing, rather narrow and specific supply chain acrros Europe	Baden-Württemberg, Cataluna, Emilia-Romagna, Flanders, Lombardy, Nord pas de Calais, South Holland, South NL, Tampere, Thuringia, Upper Austria, Wallonia, Norte, Orebro Lan, Marche, Lower Austria, Copenhagen, Central Hungary, Podkarpackie, Podlaskie (PO), Yugoiztochen (BU), Västergötland (Gothenburg Region), South East Romania, Malopolskie, West Midlands, Bavaria, South Denmark, Liguria
Affordable houses (based on automatisa-tion, redundancy of formworks)	2	WinSun (China), RMIT Institute of Technology (Australia), University of Southern California, Zhuoda Group (China), entrepreneur Lewis Yakich (3D-printed homes in Philippines)	Fimatec (Finland), DUS Architects (NL); Dshape -Monolite Ltd (UK)	IT: WASP (World Advanced Saving Project) creation of the world's largest Delta 3D-printer. AT: Lukas Lang Building Technologies and REHAU AG	Growing, large supply chains are affected across Europe	Ile-de-France, West NL (North Holland), Bratislava, Norte (?), Thessalia, South Denmark, Donoslaskie, Lancashire, North West England, Burgenland, Lubelskie, Malopolskie, Stockholm region, Emilia-Romagna, Helsinki, South East Finland

	Technology	Geographical Concentration		European Supply Chain	Potential	Regions
	Maturity	*Global key players*	*Key European players*	*Network*	*Market expectation*	
Personalized food - ingredients, structure, flavour (e.g. personalized diet, improved flavour by improved stucture)	2	3D Systems (US) produces food printers	e.g. Biozoon, Print2Taste Bocusini (Germany), TNO (Research) Netherlands, the Foodini by Natural Machines (ES), Nestle (CH) , the Choc Creator by Choc Edge (UK), MELT icepops (NL), The Magic Candy Factory (DE)	3D Ventures (UK);	Growing, has an impact also on many small firms	Beieren (DE), Bremen (DE), Galicia (ES), Thessalia (EL), Severoiztochen (BU), South-Denmark (DK), South West England (UK), Midi-Pyrénées (FR), Southern and Eastern Ireland (IRL), Groningen (NL), Malopolskie (PL), Lubelskie (PL), Nord-Vest (RO), Helsinki-Uusimaa region (FIN), Lithuania, (LT).

Source: IDEA Consult, AIT and VTT, 2015

Table 26: Application areas selected at the end of Task 1 for further research

	3DP-Application	Comment	Lead Sector [associated sectors]
1	**Tools, instruments & parts for medical devices** (i.e. tools and jigs for surgery, i.e. Kelly hemostat, needle driver, tissue forceps, retractor, scalpel handle and Metzenbaum scissors) (eventually also consider exoskeletons)	B-2-C and B-2-C, new value chains, subject to constraining regulations, and with diversity in deployment	HEALTHCARE [Possible connections to other high-precision sectors and areas (e.g. mechanic precision, optic instruments)]
2	**Personalized** car **interiors** (e.g. dashboard) **and exteriors** (e.g. wing mirrors and other non-structural components) (non-critical parts) (excl embedded electronics)	B-2-B, key to competitiveness of own value chains (e.g. weight reduction)	AUTOMOTIVE Broad outreach to other transportation sectors (Aerospace), machinery and tooling, and traditional mechanical industry]
3	**Demanding components** (e.g. gear box, powertrain parts, water pump wheel, structural parts) for cars and structural parts for aeroplanes, especially engines (e.g. turbine blades, fuel nozzles) (critical parts)	B-2-B, key to competitiveness of own value chains + impacts across value chains (e.g. automotive, machinery);, heavily regulated[341], certification challenges	AUTOMOTIVE Broad outreach to other transportation sectors (Aerospace), energy, machinery and tooling, and traditional mechanical industry
4	Inert implants, hard implants i.e. bone replacement (e.g. acetabular implants, skull implants, sternum implants) (mono-material and multi-material implants, excluding bio-absorbable implants)	B-2-B and B-2-C, new value chains, heavily regulated	HEALTHCARE [Possible connections with other sectors such as Consumer Goods - Jewelry where similar materials and processes are used]
5	Sand & metal **moulds and cores for foundries** when individual castings are needed. Plastic patterns for sand casting.	B-2-B, boosting competitiveness traditional sectors	MACHINERY & TOOLING [Broad outreach due to its horizontal character / connects to all large manufacturing sectors]
6	**Spare parts for machines** (e.g. gears, housings, buttons, fasteners)	B-2-B, strong cross-value chains impacts	MACHINERY & TOOLING [Broad outreach due to its horizontal character / connects to all large manufacturing sectors (automotive, metal manufacturing, energy, construction, agricultural machinery etc)]
7	**Home decoration** (incl. Lightning) (e.g. furniture, lightning, small statues, vases)	B-2-C (B-2-B), including embedded electronics[342], new business models (open source)	CONSUMER & LIFESTYLE [Logistics]
8	**Textiles** (adding a dimension to 2D-textiles to add functionalities, e.g. printing protective shields on firemen jackets), including embedded electronics (e.g. printing electronic tracks, 'smart textile')	B-2-C, including embedded electronics, new business models, transversal applications (transport[343], medicine, automotive etc)	CONSUMER & LIFESTYLE [Broad outreach as it relates to smart textiles to be potentially in use in government/military sectors, health, construction, transport?, automotive, aerospace, etc]
9	**Affordable houses** (based on automatisation, redundancy of formworks)	B-2-C (B-2-B), reinvigorating traditional sector	CONSTRUCTION [possible spill-overs to installations in harsh environments]
10	**Personalized food - ingredients**, structure, flavour (e.g. personalized diet, improved flavour by improved stucture)	B-2-C (B-2-B), new business models (open source). Regulated	AGRO-FOOD [Healthcare, biotechnology, bulk chemicals, consumer & lifestyle, logistics]

341 Although it is of particular importance for the aeronautic sector, regulation is also a critical factor for the car industry.
342 In the process of further exploring the potential of emerging areas, it was found that the embedding of electronics into home decoration and textile items is of importance. A key example of early development area is the one of Smart Textiles to which Additive Manufacturing could add value.
343 Through upholestry for instance.

4.1.2.3 Final selection of the 10 cases

The final selection of a short list of 10 cases (starting for the table above and the long list of 16 cases) should capture the wide variety in terms of expected impacts, sectoral coverage and business environments. All 3DP applications identified are expected to have major impacts on the industrial texture and on the overall competitiveness of industry. However, some of them may impact on a wide spectrum of value chains and sectors (e.g. in machinery) while others may create or foster the development of new value chains (heatlhcare). Some 3DP applications will create new activities and products while others will support process optimization and productivity boosts in a broad range of rather traditional sectors (e.g. 3DP cores in foundries). Some 3DP-applications will be located rather downstream the value chains (B-2-C) while others will be operating higher up in the corresponding value chains (B-2-B). Finally, there was the need to have a diversity in terms of business environment and framework conditions such as regulatory environment (healthcare). Bearing in mind this need for diversity, the research consortium proposed the following 10 cases (see Table 27) to be further studied during the case study research process:

Table 27: Top-10 3DP Applications

	3DP-Application	Comment	Lead Sector [associated sectors]	Associated regions
1	**Tools, instruments & parts for medical devices** (i.e. tools and jigs for surgery, i.e. Kelly hemostat, needle driver, tissue forceps, retractor, scalpel handle and Metzenbaum scissors) (eventually also consider exoskeletons)	B-2-C and B-2-C, new value chains, subject to constraining regulations, and with diversity in deployment	HEALTHCARE [Possible connections to other high-precision sectors and areas (e.g. mechanic precision, optic instruments)]	Flanders, Asturias, Lombardy, Emilia-Romagna, Nord pas de Calais, Aragon, Baden-Württemberg, South NL, Tampere, Wallonia, Cataluna, Thuringia, Midi-Pyrénées, Rhône-Alpes, Northern Ireland, South Denmark, Helsinki, Podlaskie
2	**Personalized** car **interiors** (e.g. dashboard) **and exteriors** (e.g. wing mirrors and other non-structural components) (non-critical parts) (excl embedded electronics)	B-2-B, key to competitiveness of own value chains (e.g. weight reduction)	AUTOMOTIVE Broad outreach to other transportation sectors (Aerospace), machinery and tooling, and traditional mechanical industry]	Baden-Wurtemberg, Aragon, Cataluna, Emilia-Romagna, Lombardy, Norte, Saxony, Slovakia (Bratislava), Bavaria, Piemonte, Thuringia, Dolnoslaskie, Podkarpackie, North/West England, Castilla, Gothenburg, Västergötland, Nord Pas de Calais, IdF(?), Moravia (CZ), Yugozapaden (BU), Argeş County (RO),
3	**Demanding components** (e.g. gear box, powertrain parts, water pump wheel, structural parts) for cars and structural parts for aeroplanes, especially engines (e.g. turbine blades, fuel nozzles) (critical parts)	B-2-B, key to competitiveness of own value chains + impacts across value chains (e.g. automotive, machinery); and B-2-B, key to competitiveness of own value chains + impacts across value chains (e.g. automotive, machinery), heavily regulated, certification challenges	AUTOMOTIVE Broad outreach to other transportation sectors (Aerospace), energy, machinery and tooling, and traditional mechanical industry	Baden-Wurtemberg, Aragon, Cataluna, Emilia-Romagna, Lombardy, Norte, Saxony, Slovakia (Bratislava), Bavaria, Piemonte, Thuringia, Dolnoslaskie, Podkarpackie, North/West England, Castilla, Gothenburg, Västergötland, Nord Pas de Calais, IdF(?), Moravia (CZ), Yugozapaden (BU), Argeş County (RO) / Aragon, Lombardy, South Holland, Upper Austria, Wallonia, Midi-Pyrénées, Piemonte, Campania, Ile-de-France, Lancashire, North West

	3DP-Application	Comment	Lead Sector [associated sectors]	Associated regions
				England, East Midlands, Podkarpackie, Hampshire
4	Inert implants, hard implants i.e. bone replacement (e.g. acetabular implants, skull implants, sternum implants) (mono-material and multi-material implants, excluding bio-absorbable implants)	B-2-B and B-2-C, new value chains, heavily regulated	HEALTHCARE [Possible connections with other sectors such as Consumer Goods - Jewelry where similar materials and processes are used]	Flanders, Asturias, Lombardy, Emilia-Romagna, Nord pas de Calais, Aragon, Baden-Württemberg, South NL, Tampere, Wallonia, Cataluna, Thuringia, Midi-Pyrénées, Rhône-Alpes, Northern Ireland, South Denmark, Helsinki, Podlaskie
5	Sand & metal **moulds and cores for foundries** when individual castings are needed. Plastic patterns for sand casting.	B-2-B, boosting competitiveness traditional sectors	MACHINERY & TOOLING [Broad outreach due to its horizontal character / connects to all large manufacturing sectors]	Baden-Württemberg, Cataluna, Emilia-Romagna, Flanders, Lombardy, Nord pas de Calais, South Holland, South NL, Tampere, Thuringia, Upper Austria, Wallonia, Norte, Orebro Lan, Marche, Lower Austria, Copenhagen, Central Hungary, Podkarpackie, Podlaskie (PO), Yugoiztochen (BU), Västergötland (Gothenburg Region), South East Romania, Malopolskie, Central Greece, Silesia
6	**Spare parts for machines** (e.g. gears, housings, buttons, fasteners)	B-2-B, strong cross-value chains impacts	MACHINERY & TOOLING [Broad outreach due to its horizontal character / connects to all large manufacturing sectors (automotive, metal manufacturing, energy, construction, agricultural machinery etc)]	Baden-Württemberg, Cataluna, Emilia-Romagna, Flanders, Lombardy, Nord pas de Calais, South Holland, South NL, Tampere, Thuringia, Upper Austria, Wallonia, Norte, Orebro Lan, Marche, Lower Austria, Copenhagen, Central Hungary, Podkarpackie, Podlaskie (PO), Yugoiztochen (BU), Västergötland (Gothenburg Region), South East Romania, Malopolskie, Central Greece, Silesia
7	**Home decoration** (incl. Lightning) (e.g. furniture, lightning, small statues, vases)	B-2-C (B-2-B), including embedded electronics, new business models (open source)	CONSUMER & LIFESTYLE [Logistics]	Galicia, Cataluna, South NL, Nord pas de Calais, Lombardy, Flanders, Ile-de-France
8	**Textiles** (adding a dimension to 2D-textiles to add functionalities, e.g. printing protective shields on firemen jackets), including embedded electronics (e.g. printing electronic tracks, 'smart textile')	B-2-C, including embedded electronics, new business models, transversal applications (transport, medicine, automotive etc)	CONSUMER & LIFESTYLE [Broad outreach as it relates to smart textiles to be potentially in use in government/military sectors, health, construction, automotive, aerospace, etc]	Galicia, Cataluna, South NL, Nord pas de Calais, Lombardy, Flanders, Ile-de-France

	3DP-Application	Comment	Lead Sector [associated sectors]	Associated regions
9	**Affordable houses** (based on automatisation, redundancy of formworks)	B-2-C (B-2-B), reinvigorating traditional sector	CONSTRUCTION [possible spill-overs to installations in harsh environments]	Ile-de-France, West NL (North Holland), Bratislava, Norte (?), Thessalia, South Denmark, Donoslaskie, Lancashire, North West England, Burgenland, Lubelskie, Malopolskie, Stockholm region, Emilia-Romagna, Helsinki, South East Finland
10	**Personalized food - ingredients**, structure, flavour (e.g. personalized diet, improved flavour by improved stucture)	B-2-C (B-2-B), new business models (open source).	AGRO-FOOD [Healthcare, biotechnology, bulk chemicals, consumer & lifestyle, logistics]	Beieren (DE), Bremen (DE), Galicia (ES), Thessalia (EL), Severoiztochen (BU), South-Denmark (DK), South West England (UK), Midi-Pyrénées (FR), Southern and Eastern Ireland (IRL), Groningen (NL), Malopolskie (PL), Lubelskie (PL), Nord-Vest (RO), Helsinki-Uusimaa region (FIN), Lithuania, (LT).

Therefore, the following applications were not retained for the final case selection[344]:

Table 28: Non-selected Applications

Sector	Application
Aerospace	Component repairing, based on directed energy deposition and hybrid technologies (e.g. aircraft engine compressor components, blisks (intergrally bladed rotors), airfoils)
Healthcare	Dental (e.g. crowns, braces and dentures), also dental devices
Machines & Tooling	Metallic mould inserts for injection moulding and die casting
Consumer life style & fashion (inluding textiles and creative industries)	Jewellery (e.g. selective laser melting of precious metals like gold and silver, plastic jewellery, casted jewellery)
Energy	Gas turbines: prototyping, repairing, direct manufacturing

344 After a meeting with the European Commission, the decision was taken to include the Application Nr 1 (Tools, instruments & parts for medical devices) in the final list presented in Table 27 in line with the arguments presented in Section 4.1.2.2. The decision was also taken to consider Demanding components for both the Aerospace and Automotive sectors which were integrated into a sole application area to be further precised during the case studies.

4.1.3 Case study approach

This section presents the results of both Task 2 and Task 3 for the ten case-studies, case by case. The case study approach was exclusively based on qualitative techniques[345]. Every case researcher from the consortium was provided with a case study protocol and case study guidelines. The cases were spread across the consortium in function of the core expertise of each partner. This process followed rational steps:

1. First, a **protocol** was elaborated and tested with a first **Pilot Case Study**. This protocol encompassed guidance and instructions for the implementation of the case study research and subsequent reporting;
2. Second, the protocol and additional oral **instructions** were communicated to the partners who could **start** to conduct their research;
3. All cases started with a first phase of **desk research** (mainly internet and literature-based);
4. The desk research was followed by **semi-structured interviews** and **written feedbacks** (124 in total[346], including several group interviews) with/from "***gate keepers***" (main companies, clusters, federations, research and technology organisations well-connected to regional eco-systems and having a broad view on their field[s] of activity) but also (potential) AM user companies;
5. Two consortium **teleconferences** were held at key moments of the process in order for the partners to exchange on cross-case insights and reiterate the relevant instructions regarding case study implementation;
6. Informal **iterations** took place along the process in order to allow the team members provide feedback to each other on their cases, including difficulties and ways to overcome them;
7. Finally, **two intermediary report** were submitted by all researchers to IDEA Consult in view of a final iteration and final integration of the adjusted case studies into the present "*Final Report*".

The interviewing process proved to be particularly difficult as many contacts refused to collaborate with our team members due to the overwhelming number of studies, surveys, etc. currently on-going at all levels of government. A second factor was also for some companies that AM is a differentiating technology and is considered too strategic to be discussed. However, our team managed to fulfill its objectives and successfully conducted the first round of case studies while following the protocol process. Main themes of investigation (see Box 30) were therefore explored and the results were reported by each member in a standard reporting template to allow cross-case comparisons.

Box 30: Main research topics

The main themes that were detailed by the case study protocol were the following:
- Definition of the application area
- Approaching the key players
- Identification of key players and market structure
- Digging further into the value chain
- First insights on drivers and barriers
- First insights on missing competencies and opportunities for joint actions/public intervention

Under these themes, the main aspects of each application area were to be studied, such as:
- Context analysis and refinement of each case area (e.g., identifying core technologies, history of the 'field')
- Composition of the value chain: players involved, activities and geographical coverage
- Insights on mechanisms underlying the value chain
- Positioning these actors in terms of supply and demand (including users and consumers)
- Positioning these actors in terms of international competitiveness (relative advantages, competitors, etc.)
- Provide first insights on...
  - Critical factors of competitiveness at value chain level and at company level
  - Connections and relations between the application and other value chains
  - Trends and possible emerging/future applications

The "*gate keeper*" approach was used to identify, approach and contact interviewees. Visible intermediaries such as large RTOs, competitiveness clusters and large companies were identified, including relevant contact points (R&D managers, marketing directors and project leaders). The contacts were first contacted by email to set up exploratory interviews. Next, the case study protocol was followed and reminders were sent by email and followed up by phone calls. As a result of the iterative use of the desk research and interviews, a depiction of each additive manufacturing value chain was produced.

[345] Some complementary techniques such as mapping techniques were mobilized to complement the qualitative analyses and provide additional findings relevant to some of the cases.
[346] Some interviews were group interviews during which more than one interviewee responded to our questions.

Content-wise, each case study started from a broad area but narrowed down the scope to focus on one specific application. The process of narrowing down the case study areas was mainly guided by the objectives of this study which is to focus on close-to-market applications with a high potential for the European regions.
Table 29 provides an overview of the final scope adopted for each application area.

Table 29: Refined application areas

	Initial 3DP-Application Area	Refined application area (case)
1	**Tools, instruments & parts for medical devices** (i.e. tools and jigs for surgery, i.e. Kelly hemostat, needle driver, tissue forceps, retractor, scalpel handle and Metzenbaum scissors) (eventually also consider exoskeletons)	**Surgical planning**[347]
2	**Personalized** car **interiors** (e.g. dashboard) **and exteriors** (e.g. wing mirrors and other non-structural components) (non-critical parts) (excl embedded electronics)	**Plastic-based car interior components**
3	**Demanding components** (e.g. gear box, powertrain parts, water pump wheel, structural parts) for cars and structural parts for aeroplanes, especially engines (e.g. turbine blades, fuel nozzles) (critical parts)	**Metallic structural parts for airplane**
4	Inert implants, hard **implants** i.e. bone replacement (e.g. acetabular implants, skull implants, sternum implants) (mono-material and multi-material implants, excluding bio-absorbable implants)	**Inert and hard implants**
5	Sand & metal **moulds and cores for foundries** when individual castings are needed. Plastic patterns for sand casting.	**Metal AM for injection Molding**
6	**Spare parts for machines** (e.g. gears, housings, buttons, fasteners)	**Spare parts for machines**
7	**Home decoration** (incl. Lightning) (e.g. furniture, lightning, small statues, vases)	**Lighting and other home decoration products**
8	**Textiles** (adding a dimension to 2D-textiles to add functionalities, e.g. printing protective shields on firemen jackets), including embedded electronics (e.g. printing electronic tracks, 'smart textile')	**3D-printed textiles**
9	**Affordable houses** (based on automatisation, redundancy of formworks)	**Affordable houses**
10	**Personalized food - ingredients**, structure, flavour (e.g. personalized diet, improved flavour by improved stucture)	**3D-printed confectionery**

The team distinguished between two main phases conducted in parallel in order to:

- Re-construct the value chain(s) segment by segment by identifying key players (companies, research and technology organisations, clusters etc.) and their activities (First Phase);
- Identifying missing competencies in the regions considered and opportunities for joint activities between them (Second Phase).

[347] 3D-printed anatomic medical models and 3D-printed surgical guides and tools

4.2 Case studies: Mapping 10 European Additive Manufacturing Value Chains

4.2.1 Surgical planning

4.2.1.1 Scoping

(i) Context

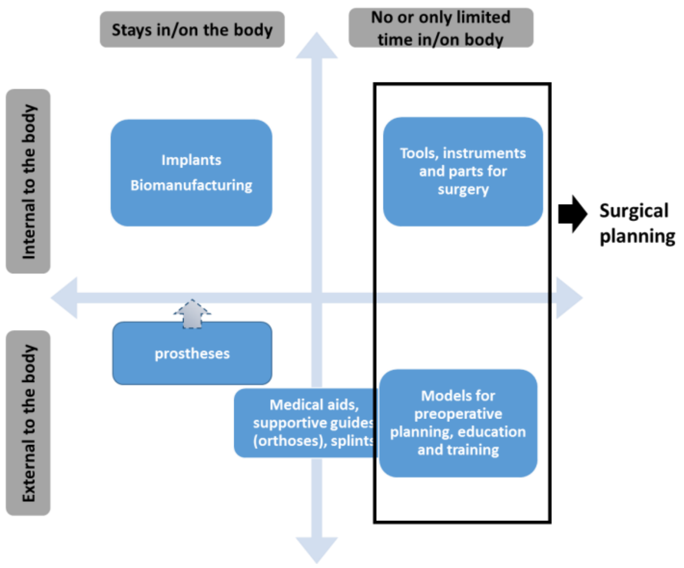
The healthcare industry is already involved in AM since 2000. Dental implants and custom prosthetics were the first applications[348]. As the printer performance, resolution and available materials increased, also the amount and the quality of the applications in healthcare increased[349]. Medical applications for 3D-printing are expanding rapidly and are expected to revolutionize health care (Ventola, 2014)[350].

The total market for additive manufacturing in the healthcare industry was 4,1 billion dollar in 2014, of which healthcare industry takes up about 490 million dollar. The total market is expected to grow to 21 billion dollar in 2020 (Wohlers, 2015), while the size of additive manufacturing in healthcare is expected to grow 25% each year between 2015 and 2020 up to 2,13 billion dollar in 2020.[351] Medical applications can be grouped into different categories[352] (see also Figure 68):

- Models for preoperative planning, education and training;
- Medical aids, supportive guides, splints, and prostheses;
- Tools, instruments and parts for medical devices;
- Inert implants;
- Bio manufacturing (tissue engineering and additive manufacturing).

The "*Models for preoperative planning, education and training*" and "*Tools, instruments and parts for medical devices*" can be grouped together under **Surgical Planning**. This application is expected to grow over the next years. A total of $644 million in value of printed components alone originating from surgical planning is expected by 2020[353].

Figure 31: Medical applications in healthcare



Source: IDEA Consult

348 Gross BC, Erkal JL, Lockwood SY, et al. Evaluation of 3D-printing and its potential impact on biotechnology and the chemical sciences. Anal Chem. 2014;86(7):3240–3253.

349 Gross BC, Erkal JL, Lockwood SY, et al. Evaluation of 3D-printing and its potential impact on biotechnology and the chemical sciences. Anal Chem. 2014;86(7):3240–3253.

350 Ventola, C. L. (2014). Medical Applications for 3D-printing: Current and Projected Uses. *Pharmacy and Therapeutics*, *39*(10), 704–711.

351 http://www.fabulous.com.co/blog/2015/11/impression-3d-medecine-medical-sante-quel-marche/

352 Tuomi J, Paloheimo K, Björkstrand R, et al. Medical applications of rapid prototyping – from applications to classification. In: da Silva Bartolo PJ, Jorge MA, de Conceicao Batista F, et al. (eds). Innovation development in design and manufacturing: advanced research in virtual and rapid prototyping – Proceedings of VR@P4, Leiria, Protugal, October 2009, pp. 701-704. Boca Raton, FL: CRC press.

353 Opportunities for additive manufacturing in surgical planning and modelling http://www.researchandmarkets.com/reports/3388719/

Additive Manufacturing is well suited for the application in the healthcare sector[354], because of following reasons:

- The large market of healthcare customers;
- Several medical devices are relatively small in size which makes it possible to produce them via common additive manufacturing systems;
- Value-dense products (combining relatively high value with relatively small physical volume) with high level of customization.

The application of additive manufacturing specifically to surgical tools and instruments provides benefits for the patient, surgeon and the hospital[355],[356]:

- Improved patient care: customized surgical tools allows the implant to be placed more precisely, which allows for a shorter surgery time and requires less anaesthetics.. In addition, it reduces the probability of further operation (less postoperative interventions). Overall, the surgery with customized instruments can be performed with less invasion than surgery with standardized instruments, reducing overall stress for the patient.
- Precision for surgeons: The design can be tailed to the specific operating situation and the functionality can be enhanced. This increases precision and decreases operating time, which in turn reduce the risk of errors, complications or infections during operation.
- Cost-effectiveness for the hospital: Disposable instruments can reduce the cost of sterilization and storage associated with conventionally manufactured instruments. A higher production and lower unit costs can be achieved via the additive manufacturing of customized instruments. Better quality can also be cost saving for healthcare by reducing surgery time and follow-up surgeries.

(ii) Application area: Surgical planning

Box 31: Accuracy in surgical planning

According to Ramasamy, Manikandan et al. (2013) "*High accuracy in planning and execution of surgical procedures is important in securing a high success rate without causing iatrogenic damage. This can be achieved by computed tomography, 3D implant planning software, image-guided template production techniques, and computer-aided surgery.*"[357]

During the first phase of the study, the area entitled "*Tools, instruments and parts for medical devices*" was selected. The choice to include this application was based on the fact that surgical and drilling guides are currently key additive manufacturing applications[358] and have a growing market expectation. Extensive web-based searches led to the observation that literature often combines 3D-printed surgical guides and tools and 3D-printed anatomic medical models (see Box 32 for more information) and labels them together as "surgical planning". It is also observed that companies often provide services for surgical planning including the 3D-printed tools and instruments as well as the 3D-printed medical models, where also the main market opportunities occur[359].

[354] 3D opportunity in medical technology: additive manufacturing comes to life. Deloitte University Press.

[355] EOS- Additive manufacturing in the medical field. https://scrivito-public-cdn.s3-eu-west-1.amazonaws.com/eos/public/b674141e654eb94c/c5240ec3f487106801eb6963b578f75e/medicalbrochure.pdf

[356] Additive manufacturing workshop Medtech 2015: presurgical planning in hospitals supported by additive manufacturing

[357] Ramasamy M, Giri, Raja R, Subramonian, Karthik, Narendrakumar R. Implant surgical guides: From the past to the present. *Journal of Pharmacy & Bioallied Sciences*. 2013;5(Suppl 1):S98-S102. doi:10.4103/0975-7406.113306.

[358] 3D opportunity in medical technology: additive manufacturing comes to life. Presentation by Dr. Mark J. Cotteleer, 22 April 2015.

[359] Opportunities for additive manufacturing in surgical planning and modelling http://www.researchandmarkets.com/reports/3388719/

Box 32: Information on 3D-printed surgical guides and tools and medical models

A **3D-printed surgical guide** is used to transfer a virtual surgical plan to real life. A surgical guide is a union of two components: the guiding cylinders or oblique holes and the contact surface[360]. The contact surface fits on an element of a patient's body (so it is temporary placed in the body). The cylinders/oblique holes within the guides transfer the plan by guiding the surgical instrument (drill or saw) in the exact location and orientation.[361] Advantages of 3D-printed surgical guides are according to Ramasamy, Manikandan et al. (2013):

- *"More precise placement of implants;*
- *Preservation of anatomic structures;*
- *High geometrical accuracy of 0,1 mm;*
- *Shorter treatment/surgery times*
- *Less invasive, flapless surgery and therefore less chance of swelling;*
- *Less post-operative strain on surgeon and patient and*
- *Transparency of material which allows seeing through the model"*

A **3D-printed medical model** is a model of a body part (e.g. organs, limbs, spine, and teeth) which is produced via additive manufacturing. It is not used inside the body.

In order to delineate the scope of the application area, the main application areas of surgical planning are explored in order to identify possible driving products.

1. Tools, instruments and parts for surgery

3D-printed instruments and tools can be common/standard or customized. The market for personalized 3D-printed surgical guides and tools can be segmented as follows[362]:

- **Cutting guides** are surgical guides which are used to temporary put over the bone (inside the body). The oblique holes within the guide transfers the plan by guiding the surgical instrument in the exact location and orientation Figure 32 provides an example of a patient-customized cutting guide which is put over the bone and indicates where the surgeons has to make the cuts.

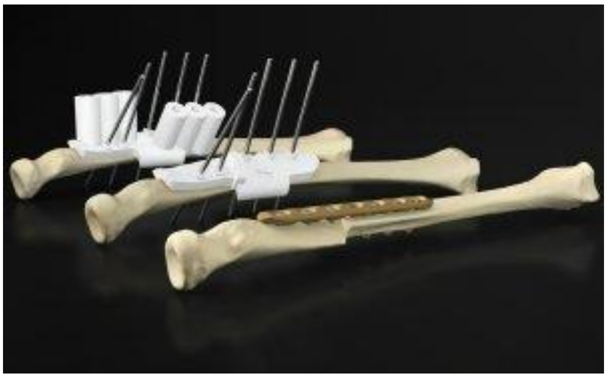
Figure 32: Patient-customized cutting guide[363]

Source: DePuySyntheses Joint Reconstruction

- **Drilling guides** are surgical guides which are used to temporary put over the bone (inside the body). The cylinders within the guide transfers the plan by guiding the drill in the exact location and orientation. Figure 33 provides an example of a patient-customized drilling guide which is put over the bone and indicates where the surgeon has to drill during the surgery.

360 Ramasamy M, Giri, Raja R, Subramonian, Karthik, Narendrakumar R. Implant surgical guides: From the past to the present. *Journal of Pharmacy & Bioallied Sciences*. 2013;5(Suppl 1):S98-S102. doi:10.4103/0975-7406.113306.
361 SurigGuid Cookbook: Drill guides for every case scenario http://dental-depot.com/materialise/pdf/Cookbook.pdf
362 Opportunities for additive manufacturing in surgical planning and modelling http://www.researchandmarkets.com/reports/3388719/
363 http://synthes.vo.llnwd.net/o16/LLNWMB8/INT%20Mobile/Synthes%20International/Product%20Support%20Material/legacy_DePuy_PDFs/DPEM-ORT-0912-0237-1_9075-97-000_LR.pdf

Figure 33: Patient-customized drilling guides[364]



Source: Mobelife

The use of customized cutting and drilling guides has several advantages[365]: (1) Precisely transfer of virtual planning into the surgical environment; (2) Reduce operating time and (3) Improves the precision.

- **Other surgical tools and instruments** which can be manufactured via additive manufacturing are amongst others customized scalpels. Instruments can be customized to the surgeon or to the patient, increasing the precision during surgery and reducing the surgery time. It is also possible to create common, standardized instruments via additive manufacturing: e.g. civilian and military organisations have created a basic surgical kit (containing a kelly haemostat,, needle driver, tissue forceps, retractor, scalpel handle and Metzenbaum scissors etc.) which was pre-sterilized and based on polymer using additive manufacturing[366] (see Figure 34). The idea is that additive manufactured common instruments can help to overcome challenges related to the treatment of battlefield trauma such as the logistical challenges of providing sterile surgical instruments.

Figure 34: Printed basic surgical kit[367]

As the guides and instruments come in contact with the bone, they have to be produced out of biocompatible material which can be sterilized and have to be approved for short-term skin, blood or mucosal contact[368]. Materials that can be used are: "*ABS-M30i or ULTEM 9085 (FDM), MED610, FullCure 630 or FullCURE 655 (PolyJet); or VisiJet Crystal, Stoneplast and Clear plastic materials (SLA) which have USP Class VI certified materials*" (Srivatsan and Sudarshan, 2015)

2. Models for preoperative planning, education and training (medical models)

3D-printed medical models are 3D-models of a body part (e.g. organs, limbs, spine and teeth) which are produced via additive manufacturing. They are often produced in polymers but also steal or other materials such as rubber. The different applications are summarized below:

364 http://ortho.materialise.com/

365 Naghieh, Saman, Badrossamay, M. and Foroozmehr, E. Frabriation of cutting guides for Oral and maxillofacial bones by additive manufacturing techniques: case studies. Presentation at 3rd congress of Iranian oral and maxillofacial pathologist 29-31 July 2015, Iran-Isfahan

366 3D opportunity in medical technology: additive manufacturing comes to life. Presentation by Dr. Mark J. Cotteleer, 22 April 2015.

367 Shayne Kondor, CAPT Gerald Grant, Peter Liacouras, MAJ James R. Schmid, LTC Michael Parsons, Vipin K. Rastogi, Lisa S. Smith, Bill Macy, Brian Sabart and Christian Macedonia. On demand additive manufacturing of a basic surgical kit. *J. Med. Devices* 7(3), 030916 (Jul 03, 2013)

368 Additive Manufacturing: Innovations, Advances and Applications. T.S. Srivatsan,T.S. Sudarshan, september 2015.

- **Surgical preparation**: A tangible 3D-printed medical model of a patient's anatomy helps surgeons to prepare and simulate surgery. Tangible 3D models are more instructive than MRI or CT scans as they are viewed on a flat screen (Gross et al, 2014)[369]. Figure 35 provides a picture of 3D-printed models which were used for preparing the surgery for splitting conjoined twins.

Figure 35: 3D-printed surgical planning models of conjoined twins (left) with bone structure and brain vasculature (right), courtesy of Medical Modeling, Inc.

Source: Wohlers 2015

- **Training and education**: Additive manufacturing allows rebuilding and producing anatomical, high complex models. The models allows assistant surgeon's to be trained close to the reality without possible damage to the patient[370]. According to Banks (2013) it is even preferred to do surgical training on 3D-printed model over cadavers, as cadavers are more scarce and costly and often lack the appropriate pathology[371].

Figure 36: Training and education model by Encoris

Source: http://www.3ders.org/articles/20151031-clear-3d-printed-skeleton-firm-encoris-boasts-annual-sales.html

- **Customer communication**: According to Dr. Jason Koh, an orthopedic surgeon, 3D-printed models provide benefits also for the patient: "*You can better explain the situation to the patient using these tools when they can hold something like this while you talk. They can see the situation. It can sometimes help ease a patient's mind when they also have a better understanding of what's going on*."[372]

369 Gross BC, Erkal JL, Lockwood SY, et al. Evaluation of 3D-printing and its potential impact on biotechnology and the chemical sciences. Anal Chem. 2014;86(7):3240–3253.
370 Additive manufacturing workshop Medtech 2015: presurgical planning in hospitals supported by additive manufacturing.
371 Banks J. Adding value in additive manufacturing: Researchers in the United Kingdom and Europe look to 3D-printing for customization. IEEE Pulse. 2013;4(6):22–26
372 https://www.asme.org/engineering-topics/articles/bioengineering/medical-training-with-3d-printing

4.2.1.2 Identifying value chain components

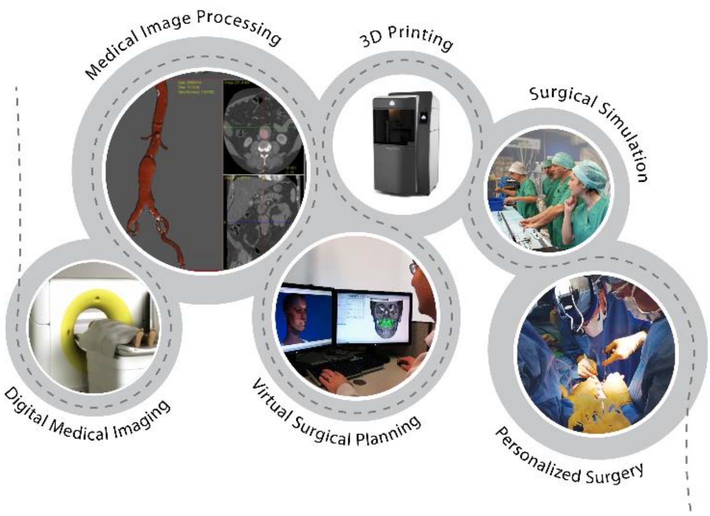
(i) Identification of key players and usage of Additive Manufacturing for surgical planning

Additive manufactured surgical planning material is already on the market and sold by different types of companies. As indicated, the focus is on two segments where 3D-printing technology is used in surgical planning: tools and instruments for surgery and 3D-printed models. Important players in the market for the production of 3D-printers are 3Dsystems (US), Stratasys (IL), EnvisionTEC (DE), Arcam (SE) and service providers such as Materialise (BE)[373]. Some of these companies are also service providers (e.g. Materialise via Mobelife and 3Dsystems via Layerwise). There are different examples of successful production and use of surgical planning as discussed below.

Tools, instruments and parts for surgery

3DSystems is already involved in surgical planning and personalized medical solutions for almost two decades. 3DSystems is committed to build an end-to-end Digital Thread for Personalized Surgery (Figure 37) offering healthcare-centric 3D-printing and 3D visualization technology. Their digital surgical tools include accurate 3D-printed anatomical models; advanced virtual reality simulators; direct metal printing for implants and instrumentation; and personalized 3D-printed surgical guides. The 'Digital Thread for Personalized Surgery' of 3DSystems is a proprietary workflow guiding the entire process from patient medical imaging through surgical outcomes, enabling the transition from the virtual world to the physical with perceptual design tools and software, surgical simulation and 3D-printed surgical guides and models[374].

Figure 37: End-to-end Digital Thread for Personalized Surgery



Source: 3D Systems[375]

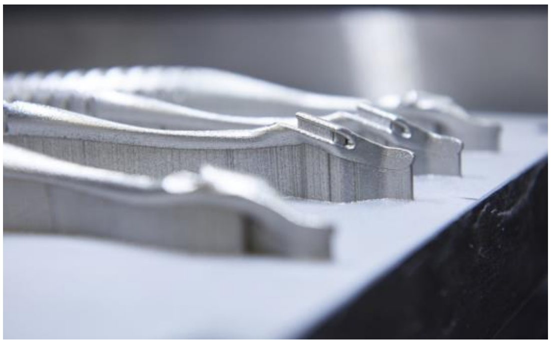
[373] 3D-printing in medical applications market (medical implants, surgical guides, surgical instruments, bio-engineered products) – global industry analysis, size, share, growth, trends and forecast. Transparency Market Research. September 15th, 2015.

[374] http://www.3dsystems.com/solutions/healthcare

[375] http://www.3dsystems.com/solutions/healthcare

Stratasys's printers allow to print surgical kits customized to patient anatomy. Using strong sterilizable and biocompatible materials, it is possible to 3D-print custom molds and cutting guides for more accurate cuts or to shape patient implants prior to a procedure using[376]. Stratasys has also collaborated with a new medical company called DanaMed in order to create a 3D-printed tool that could change the face of ACL knee reconstruction surgery. The medical company of Dr. Piasecki, DanaMed, designed the Pathfinder (Figure 38), a tool that will allow for much more flexibility and accuracy in ACL reconstruction surgery. After creating the first iteration of the surgical tool from plastic and testing it on anatomical models, Dr. Piasecki went to Stratasys Direct Manufacturing's Direct Metal Laser Sintering (DMLS), where the tool the Pathfinder was produced in the biocompatible and mechanically sound Inconel 718 alloy. By utilizing Stratasys' in-house DMLS systems, DanaMed was able to manufacture the tool's intricate geometry, while keeping the production cost low.[377]

Figure 38: Pathfinder – tool for ACL knee reconstruction surgery



Source: http://3dprintingindustry.com/2016/01/08/new-3d-printed-surgical-tool-a-breakthrough-for-acl-reconstruction-surgery/

Additive manufacturing is also used to produce instruments for brain surgery which requires devices and instrumentation that are manufactured to the highest levels of precision. Deep Brain Stimulation (DBS), which treats acute symptoms of various diseases, targets areas of the brain that are measured in millimetres. FHC - a worldwide leader in innovative neuroscience products for more than 40 years—collaborates with a leading neurosurgeon to transform traditional stereotaxy using a 3D-modelling process based on each patient's anatomical coordinates. The first application of this new STarFix technology is the, patient-matched, frameless microTargeting™ Platform (Figure 39), which offers greater patient comfort, increased accuracy and time savings in the operating room. Using the FORMIGA P 100 (from EOS) to laser sinter the Platform, FHC achieves precision results at reduced costs within record delivery times.[378]

Figure 39: Patient and procedure customized Platform illustrating flexibility of form possible with SLS fabricated Platform

Source: FHC, Inc[379]

[376] http://www.stratasys.com/industries/medical/personalized-patient-care#sthash.sXEIO0WI.dpf
[377] http://3dprintingindustry.com/2016/01/08/new-3d-printed-surgical-tool-a-breakthrough-for-acl-reconstruction-surgery/
[378] http://www.eos.info/press/customer_case_studies/fhc
[379] http://www.eos.info/press/customer_case_studies/fhc

Besides brain surgery, also surgery on the human spine is an exact and delicate procedure. The precision and reliability of the instruments used by the surgeon are critical. As minimally invasive surgery (MIS) becomes one of the fastest-growing areas in spine treatment, orthopaedic surgeons are demanding increasingly sophisticated tools. These must be sized for greater access and control through smaller incisions, made strong enough to cut through cartilage and bone, and built from materials that are biocompatible. DePuy Spine has worked and partnered with leading clinicians and researchers for over 20 years to advance knowledge of both professionals and patients in addressing spinal pathologies and to develop products to treat spine disorders. They have applied EOS technology to produce additive manufactured instruments such as the plate bender, which is used to contour plats for spinal surgery (*Figure 40*). [380]

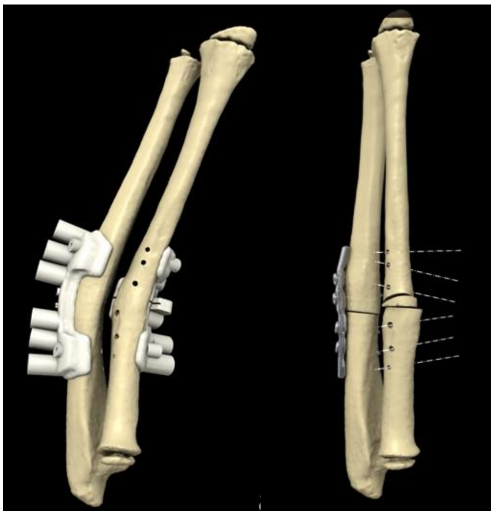
Figure 40: Prototype of a Plate Bender, used to contour plates for spinal surgery

Source: DePuy Spine

Dr. Frederik Verstreken (Monica Hospital, Antwerp, Belgium) performed a corrective osteotomy of the forearm using 3D computer planning and patient-specific guides (of Materialise) and plates on a 7-year old boy.

Figure 41a shows a picture of the drilling (left) and cutting (right) guide prepared before and used during the surgery. The patient specific surgical guides were built to fit the unique shape of the patient's bone, clearly indicating the drill holes or osteotomie defined in the surgical plan. Figure 41Figure 41b shows the patient-specific plates with pegs which was used during the surgery to fix the box again.

Figure 41: (a) Drilling and cutting guide design based on initial anatomy and planned outcome (b) Illustration of patients-specific plates with pegs which follows the contours of the bone.



Source: Video on patient-specific guides and plates for a double forearm malunion case[381]

380 http://www.eos.info/press/customer_case_studies/depuy-spine

381 http://ortho.materialise.com/cases/patient-specific-guides-and-plates-double-forearm-malunion-case

Models for preoperative planning, education and training (medical models)

There are multiple case examples where 3D-printed anatomical models are used to prepare surgery (Ventola, 2014). As with the personalized tools, the use of a 3D-printed neuroanatomical model can be very helpful for neurosurgeons. The advantage are that the complex, sometimes obscured relationships between cranial nerves, vessels, cerebral structures, and skull architecture is more easy to interpret contrary to using solely radiographic 2D images[382] Another example is a liver transplants at Japan's Kobe University Hospital which prepared by using 3D-printed models. To determine how to best carve a donor liver with minimal tissue loss to fit the recipient's abdominal cavity, replicas of a patient's organs were used[383].

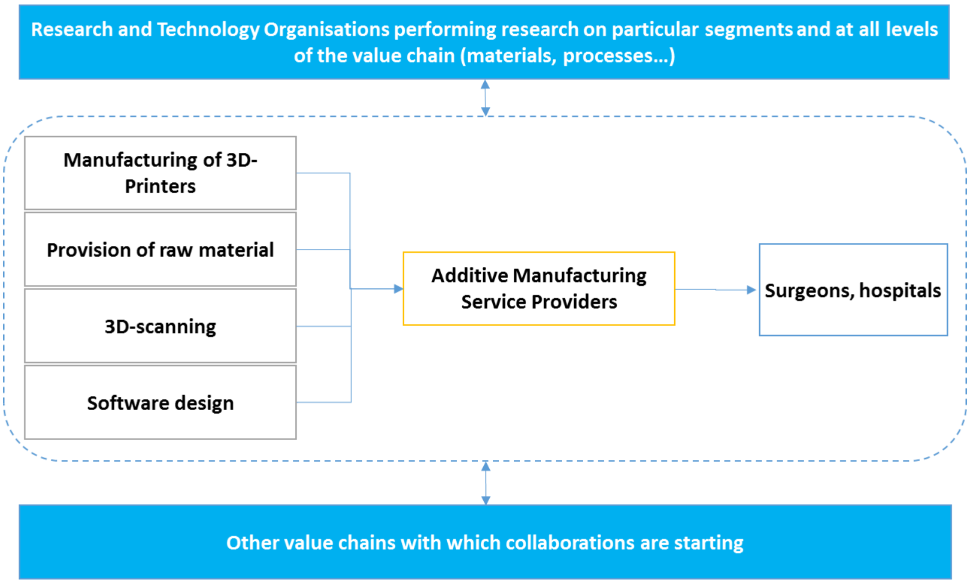
Deloitte and MeDtech (2015) have identified some best practices with respect to 3D-printed medical models[384]:

- "*Medical schools using AM anatomical models as substitute for cadavers, achieving 75% cost savings;*
- *Hospitals train surgeons using lifelike customizable AM models, enhancing trainee's ability to perform complex surgeries;*
- *Researchers use AM color model of respiratory virus to better understand its structure*".

(ii) Composition of the value chain

In order to understand the status of additive manufacturing in surgical planning industry, the value chain is constructed positioning the key actors that are active in and outside Europe.

Figure 42: Main segments of the surgical planning additive manufacturing value chain



Manufacturing of 3D-Printers
EOS (DE), Materialise (BE), Layerwise (part of 3Dsystems) (BE), Arcam (SE), EnvisionTEC (DE), SLM solutions (DE), Voxeljet (DE) and Renishaw (UK) are large 3D system providers for the healthcare sector. Some important non-EU providers are 3Dsystems (US), Stratasys (IL) and ExOne (US).

Provision of raw material
The materials are provided by companies specializing in different areas. In the field of surgical planning, the most important material entail metal and polymers. Important for the production of tools and instruments for surgery is the biocompatibility of the material. For the 3D-printed medical models, the biocompatibility is not relevant, and a larger variety of materials are used.
For the production of surgical guides, the following materials, which are USP Class IV certified materials, can be used (Srivatsan and Sudarsha, 2015)[385]:

- ABS-M30i or ULTEM 9085 (FDM)
- MED610, FullCure 630 or FullCure 655 (PolyJet)
- VisiJet Crystal, StonePlast or Clear plastic materials (Stereolithography, SLA)

Stratasys (IL) is an important supplier of the material ABS-M30i, ULTEM 9085, MED610, FullCure 630 and FullCure 655. 3Dsystems (US) is an important supplier of VisiJet Crystal, StonePlast or Clear plastic materials.

[382] Klein GT, Lu Y, Wang MY. 3D-printing and neurosurgery—ready for prime time? World Neurosurgery. 2013;80(3–4):233–235
[383] Klein GT, Lu Y, Wang MY. 3D-printing and neurosurgery—ready for prime time? World Neurosurgery. 2013;80(3–4):233–235
[384] http://www.medteceurope.com/sites/default/files/2.mark_cotteleer_-_presentation_to_share_0.pdf
[385] T.S. Srivatsan, T.S. Sudarshan. Additive manufacturing: innovations, advances and applications. 2015, pp 377 CRC press

3D-scanning

Similar to the value chain of hard and inert implants, the CT (computed tomography) and cone-beam computed tomography (CBCT) are used. Magnetic resonance imaging (MRI) is also used, mainly for dental applications (Wohlers, 2015).

Software design

Specialized software is used to transform the medical image data produced by CT scans (2D images to 2,5 or pseudo-3D by using a "slicing technique"), specialized software is needed. The most common format of medical imaging is DICOM, an open-source standard. In addition, it is necessary to export the medical image data to a suitable additive process format (STL) (Wohlers, 2015).
Specifically for applications in the healthcare sector there are image-processing software products such as Mimics (Materialise) and Osirix (Open Source) (see Table 33).

Table 30: Overview of medical image-processing software products

Product	Manu-facturer	Country	Description
Mimics	Materialise	Belgium	Imports from various medical-imaging modalities, processing the images, and exports to STL and native additive-manufacturing formats
3Matic	Materialise	Belgium	Allows for digital design by manipulation of STL files: useful in design and manufacture of complex prosthetic devices
RapidForm	3D Systems	United States	Imports DICOM image data, processes the images, and exports to various formats
Amira	Vision Imaging	France and Germany	Imports from various medical-imaging modalities, processes the images, and exports to STL format
Osirix	Open Source	Switzerland	Imports from various medical-imaging modalities, processes the images, and exports to STL format: allows for image fusion between different scan types
Geomagic Studio	3D Systems	United States	Imports CBCT images and provides tools for the design of dental-related prosthetics.

Source: *http://www.wohlersassociates.com/medical2015.pdf*

Some of the companies also prefers to develop medical image-processing software in-house. This allows them to control price but also provides more flexibility to different features.

There is also a large variety of open-source medical image-processing software available.

Additive Manufacturing Service Providers

An additive manufacturing service provider is a company which provides additive manufactured surgical planning to their customers. Two different types of additive manufacturing service providers can be distinguished.

- There are some companies which are historically the main providers of surgical planning. These companies are often still much focused on traditional manufacturing but offer complementary services with additive manufacturing technology. Some big players are Johnson and Johnson (US), Stryker (US), Zimmer Biomed (CH), Smith and Nephews (US)[386] and Siemens healthcare (DE). Other companies are Encoris (Nl), 3D-side (BE), Lima Corporate (It).
- There are also companies which focus on additive manufacturing technology and provide services in different industries: Materialise (BE), Renishaw (UK), Stratasys (IL), Xilloc (Nl) and Oxford Performance materials (UK).

Hospitals and surgeons

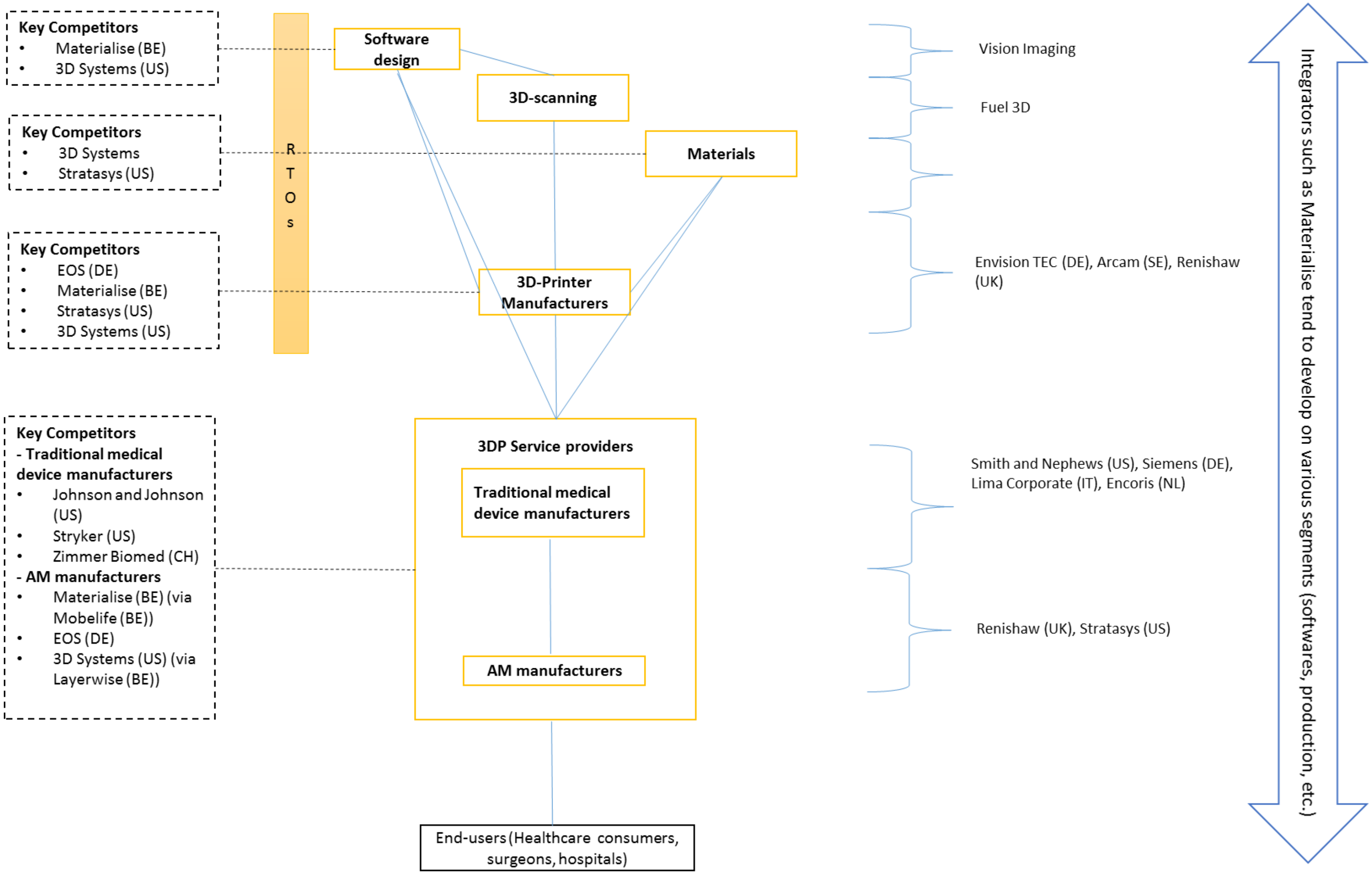
The surgical guides are provided to hospitals where surgeons uses them to perform surgery on a patient. During the interviews it was indicated that the surgeon plays an important role in the choice of tools: traditionally manufactured versus additive manufactured tools. At the moment, most surgeons still prefer to work with traditionally manufactured tools. It is important to inform surgeons about the different options though, as customized tools might reduce surgery time, beneficial for the patient and the cost-structure of the hospital.
As the use of 3D-printed medical models is becoming more and more integrated at universities for education and training of surgeons, there is the expectation that new surgeons will be more acquainted to additive manufacturing technologies and possible applications. Although the use of surgical guides has already grown heavily in the last five years, an increase in the use can be induced by a new generation of surgeons.

386 http://www.smith-nephew.com/about-us/what-we-do/orthopaedic-reconstruction/

Research and Technology Organisations
Several RTO's are doing research in the field of additive manufacturing for medical devices. New and improved medical applications often occur from interdisciplinary collaboration between the orthopaedics department and the engineering department at universities. Research at universities with respect to surgical planning mainly focusses on surgical guides (drilling and cutting guides) and solutions for specific orthopaedic surgeries. With respect to the 3D-printed medical modelling, there is some interest from universities in material research; i.e. multi-materials and bio-degradable materials.

Connections with other value chains.
There are limited connections to other industries. Within the healthcare sector, it is obvious that the value chain of the implants is connected to the one from the surgical planning. For the surgical guides, the biocompatibility of the used materials is important as with the implants. Research on materials for healthcare applications can thus be useful for surgical guides. As material and 3D-printing equipment need to be compatible, there is also some interconnectivity between implants and surgical planning applications. Some large players offer a broad portfolio of services including solutions for both implants and surgical planning, e.g. Stratasys (IL), Materialise (BE), 3Dsystems (US), EOS (DE) … Up to now, the connections to non-healthcare value chains are limited.

Figure 43: Illustration of the surgical planning additive manufacturing value chain



Source: IDEA Consult, 2016

Note: the names of the organisations mentioned are only included for illustration purposes and no colour code was applied – colours codes were only added to make the figure more readable.

(iii) Functioning of the value chain and critical factors

Deloitte and Medtec (2015)[387] constructed a framework in which they present the impact of additive manufacturing on the healthcare industry (the same framework is applicable in the case "inert and hard implants"). Additive manufacturing makes it possible to break existing performance trade-offs in two fundamentals ways:

- Additive manufacturing reduces the capital required to achieve economies of scale: less capital is required to reach minimum efficient scale for production, lowering the barriers to entry to manufacturing for a given location. This shapes the **supply chain**.
- Additive manufacturing increases the flexibility and reduces the capital required to achieve scope: more variety of products per unit of capital can be produced, reducing the cost of production changeovers and customization and the overall capital required. This shapes the **product (design)**.

The framework outlines four tactical paths that companies can take when wanting to improve product and/or supply chain competitiveness via the use of additive manufacturing technologies. The paths take into account the capital versus scale and scope relationship, and as such distinguish between the product and supply chain impact.

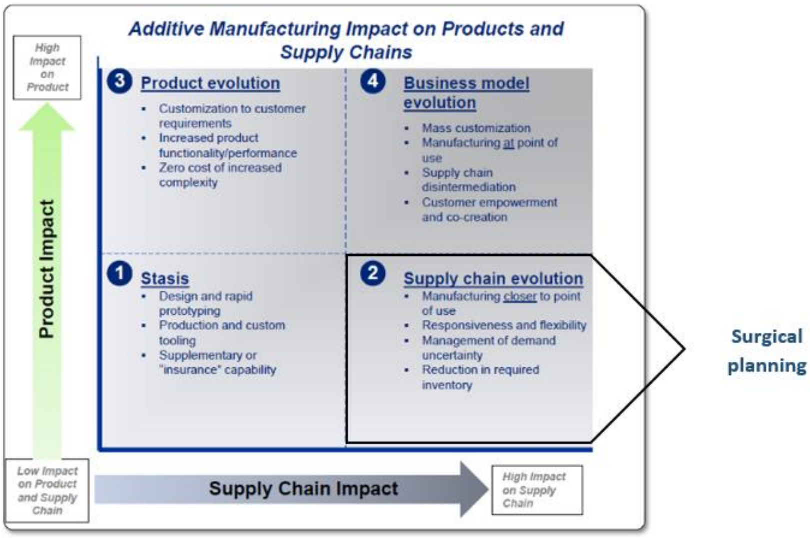
Path 1: Companies want to improve performance without alternations in supply chains or products;
Path 2: Companies want to improve performance via alternations in supply chain but not in products;
Path 3: Companies want to improve performance via alternations in products but not in supply chains;
Path 4: Companies want to improve performance via alternations in both products and supply chains.

Using additive manufacturing technology for surgical planning applications has an impact on competitiveness of the supply chain and can induce the following changes (see also):

- Manufacturing closer to the point of use;
- Responsiveness and flexibility;
- Managing uncertainty;
- Improved visualization and clinical outcomes;
- Opportunities to take on more complex cases.

Additive manufacturing can thus drive supply chain efficiency and influence inventory levels and distribution (Deloitte, 2014).

Figure 44: How will additive manufacturing impact industry



Source: Deloitte Services LP. 2015

These possible changes in the supply chain could in the future have a clearer impact on the value chain. Especially the item on "*manufacturing closer to the point of use*" should become a point of attention. It might be possible for hospitals to invest in additive manufacturing equipment to be able to produce their own 3D-printed medical models. Instead of buying equipment, in the future it might also be possible to put up a leasing model. This might have a disruptive effect on the value chain with respect to the additive manufacturing service providers.

387 3D opportunity in medical technology: additive manufacturing comes to life. Presentation by Dr. Mark J. Cotteleer, 22 April 2015. And http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-medtech/

4.2.1.3 Missing capabilities

(i) Regional dimension

Europe, North America and Asia Pacific are key markets in global 3D-printing in medical applications. According to Transparence Market Research (2015), the dominant market will in the future shift from North America to Europe as the economic conditions in Europe are more conductive, stimulating market growth, and possibly allowing Europe to surpass North America by 2019[388].

The existing capabilities are mainly concentrated in Western European countries and some links can be observed between the players at stake or the regions from which they operate.

Belgium has a pioneering position in additive manufacturing since 1990[389]. The number of companies that enters the additive manufacturing market is growing and existing companies also explore the possible use of additive manufacturing for traditionally produced products.

- Sirris, a collective centre for the technological industry has 25 years of experience with additive manufacturing in material and production methods. It comprises 140 technology experts spread over 7 sites in Belgium, serving 5000 customers of which 80% SMEs.[390] Among others initiatives, Sirris managed the BIOFACT project aiming at improving knowledge and know-how concerning mechanical prostheses and orthotics, controlled by the brain. Sirris developed innovative prostheses by means of 3D-printing: a leg prosthesis controlled by a headset which analyses the brain waves has been created, next to a bio-manufacturing platform, comprising the additive manufacturing equipment and simulation tools to conceive bio-medical devices.Other related interventions have been related to pre-surgical planning and maquettes, further than scaffolds in ceramics for spine surgery [391].
- KULeuven, department of Mechanical engineering, is mainly performing research on stereolithography (SLA) and selective laser sintering and melting (SLS/SLM). "*A patented SLA liquid curtain recoating system has reduced the time needed for depositing successive liquid layers by a factor of ten, yielding a proportional reduction in production time. Major advances are made in direct laser sintering of high strength metal powders like steel, titanium, tungsten carbide and other materials. The application of these material addition processes to actual manufacturing (so- called Rapid Manufacturing) is mainly focusing on tool manufacturing (Rapid Tooling), aerospace manufacturing (a/o production of light-weight hollow structures) and medical prostheses (dental prostheses, scaffolds). A major break-through has been achieved in rapid manufacturing by moving from SLS to SLM*'.[392]
- Melotte transformed itself from a mould builder into an important player in metal additive manufacturing. Melotte offers different applications of which personalized surgical instruments is one[393].
- Materialise is a spin-off of KU Leuven and is market leader in additive manufacturing software and solutions. It offers patient-specific or customer-specific solutions such as surgical guides. Mobelife NV, also located in Flanders, is part of Materialise's medical applications. Mobelife offers a completely customized product development process for patient-specific orthopedic implants.[394]
- Layerwise is a spin-off of KU Leuven and is now part of 3Dsystems[395]. It focusses exclusively on additive manufacturing of metal parts (Direct Metal Printing, DPM) and invests a lot in R&D to push the boundaries of additive manufacturing. It targets serial production and prototyping. Layerwise provides instrumentation used for orthopaedic, spinal and cranio-maxillofacial applications.

During the interviews and desk research, other regions are identified (see also case study on "inert and hard implants").

- **Germany (Bavaria, Baden-Württemberg)** is an important country when it comes to metal additive manufacturing. In Germany there are some large system and material suppliers concentrated: Concept Laser, SLM solutions, Realizer, Voxeljet and EOS. An important research performing organisations is Fraunhofer. Important German medical device companies are Siemens Healthcare and Bayer.
- In **Asturias (Spain),** there is a cluster on additive manufacturing and different companies active in the healthcare sector. Their application focus is more on implants in general than on surgical planning.
- In **Denmark**, there is WelfareTech which operates a national cluster. It is a hub for innovation and business developments in healthcare, homecare and social services. They are a membership organisation with members from private industry, public organisations and research and education institutions[396]. Additive manufacturing interest in this area mainly concerns prosthetics and orthosis (also exoskeletons). The interest towards customized additive manufactured surgical tools and models seems to be rather limited.

[388] http://www.medgadget.com/2015/09/3d-printing-in-medical-applications-market-future-trends-and-forecast.html
[389] Additive manufacturing on its way to industrialisation: a game changer. Cecimo magazine
[390] http://www.sirris.be/nl
[391] http://www.slideshare.net/sirris_be/2014-0123sotabioprintingsirris
[392] https://www.mech.kuleuven.be/pp/research/rapidprototyping
[393] http://www.melotte.be
[394] http://mobelife.be/company
[395] http://www.layerwise.com/
[396] http://en.welfaretech.dk/

- In **Emilia Romagna (Italy)**, and in Italy in general, additive manufacturing of tools and instruments for surgery appears to be started. There are only limited experiences so far, but some increases in exploitation are possible in the coming months. In this respect it is very important that surgeons are not resistant to the use of new technologies, otherwise the market uptake of customized tools and instruments (produced by additive manufacturing technology) will be difficult.

(ii) Barriers to the uptake and further deployment of AM in the value chain

When compared to traditional techniques, AM appears quite expensive[397]. When taking the whole surgical process into account, AM can lead to cost savings. One should however remain cautious regarding the potential of AM to applications such as surgical guides as barriers to its further deployment remain.

Technology-related barriers

- The **price** of a printer and related materials also stand up as a barrier to the further adoption of AM by surgeons and hospitals. AM requires a large up-front investment. Most of the hospitals have budget constraints and priorities that can to some extent exclude the use of AM for surginal planning.
- The accuracy (geometry) and fidelity (representative in real practice) of the tools can still be improved.
- The focus of surgical planning is still on hard materials. The body consists of a lot of soft tissue though. Medical models consisting of elastomeric type of material is mainly in a research stage. Medical models will also improve a lot if multimaterial printing becomes more finetuned.
- AM reached a level where it can reproduce the complexity and unicity of human organs. It is however concerned with a main technical limitation which is related to the difficulty to replicate all relevant properties of the surgical operation. Besides the simple geometry, the responsiveness of each tissue to a particular move associated to a living body are to be taken into account. **Current processes and materials available do not provide this level of precision** yet, which is also a limitation to the preparation procedure. Thus further development of the surgical precision tools and processes are still required.
- Related to new technological advances, is the rise of virtual applications. Virtual models are improving in that respect and mainly when coming to 3D models. Therefore, **the rise of virtual planning** constitutes a possible barrier to the further expansion of AM surgical guides.

Knowledge and information

- **Awareness** is still lacking at the level of possible users. Surgeons and hospital workforce are missing relevant information on the pros and cons of Additively Manufactured surgical guides. This limits the speed of deployment of AM in the field.
- The lack of **multidisciplinarity** is also a weakness that is hampering the further deployment of AM in the field. Additive manufacturing in healthcare often requires insights from engineers, surgeons and radiologists. Collaboration and exchange of experiences between the different actors is therefore required but is often still missing.
- The lack of multidisciplinarity relates to an important barrier: the **lack of skills and training**. This particularly applies to knowledge areas such as:
  - raw material development
  - computer-aided design
  - building operation
  - maintaining AM machines
  - supply chain and project management[398].

All these skills are often not present within the hospital.

Technological knowledge

- **Multidisciplinary skills are** still very scarce. As indicated, additive manufacturing in healthcare requires insights from engineers, surgeons and radiologists. Combining skills from these three disciplines will be beneficial for the update of advanced manufacturing in surgical planning.
- It was indicated in the interviews that, compared to Europe, US companies better **manage to implement technology itself in service design**. They manage better to implement the existing processes into a business process. In this respect, it is important to deal with the issue of software planning and to reduce the overall complexity of the planning.

In the context of medical tooling, IPR are not yet seen as a barrier, even if mass customisation could bring considerable changes. The spread of AM to a large network of hospitals after technical limitations have been overcome could lead to larger quantities of AM products in the field, but the liability issue would still limit the ability of key players to take over the AM of key tools and instruments.

[397] Ramasamy M, Giri, Raja R, Subramonian, Karthik, Narendrakumar R. Implant surgical guides: From the past to the present. *Journal of Pharmacy & Bioallied Sciences*. 2013;5(Suppl 1):S98-S102. doi:10.4103/0975-7406.113306.

[398] 3D opportunity in medical technology: additive manufacturing comes to life. Deloitte University Press, 2014.

4.2.1.4 Conclusions: opportunities for public support

There is an increasing demand for surgical planning relevant to AM[399]. The sector is characterized by a high level of fragmentation at the level of (potential) users but the current AM capabilities can clearly be identified as being located in Western Europe where organizations such as SYS (branch of the US-based Stratasys[400]) develop relevant printers based on technologies such as fused deposition modelling. Although healthcare companies are classically Anglo-Saxon businesses, AM providers that entered the area rather come from Germany, Sweden and other Western-European countries[401]. New business models are even arising from European actors such as Materialise (Flanders) which introduced in 2014 a new solution integrating "*the Mimics® Innovation Suite software, 3D-printing services, training and consultation*" to support hospitals in the design of surgical models[402]. Future application areas were identified:

- Currently, most 3D-printed surgical planning concerns hard materials. The majority of the body is soft tissue though. The materials for e.g. cardiovascular and gastronintestinal models requires elastic properties from the material.
- There is still a lot of potential in modelling and simulation of surgery. Very important is the identification of the problem and the quantification of the problem. 3D-printing can add value for the healthcare sector here. Overall there is still a lot of market potential for printed anatomical models, which are advancing into a new hierarchical value structure. This due to large range of 3D-printers that became available: from low cost printers up to advanced, highly realistic, multi-material professional systems. [403]
- The need for 3D print enabled surgical planning services are induced by the availability of 3D-printed models and surgical guides/tools and need for software and speciality service providers. [404]

A key missing capability was identified in the context of this value chain: currently, a lot of the effort in healthcare with respect surgical planning is still focused on hard tissue such as maxillofacial reconstruction and orthopaedic applications. The majority of the body consist of **soft tissue** though, which requires more elastic properties of the material. A main missing capability in surgical planning is the availability of surgical models consisting of elastomeric type of materials (polymer) which have these elastic properties. Very important for these models is their fidelity. The availability of these models focussing on soft body tissues such as cardiovascular and gastrointestinal models, would allow for high fidelity training to de-risk training new practicioners.

When considering the obstacles to the deployment of AM for surgical planning, one can derive policy implications that take into account the structure and upcoming trends in the area. These are listed below:

1. The first policy implication relates to the need for **improving skills**. Skills are particularly needed in areas such as:
    a. (raw) material properties and development (accuracy and fidelity of the material)
    b. computer-aided design
    c. building operation
    d. maintaining AM machines
    e. supply chain and project management (allowing to identify opportunities to bring production in-house using additive manufacturing, identify suppliers that are developing AM competence, consider possibility of coproduction with suppliers and customers…)[405].
    f. Legal skills (awareness of IP issues and regulatory regimes for new production processes and materials).[406]

These skills can be obtained via **education and/or training**. Multidisciplinary training will allow to better understand the different angels that are needed to implement 3D-printing in healthcare applications (surgeons, radiologists and engineers). But more overall there is certainly a need for training to use 3D-printing systems. The current printers are not sufficiently usersfriendly yet. The userinterfaces are often still complex and oriented to/designed by researchers (difficult to use for companies). Training can be organized at the national level, and a coordinated EU approach can improve the diversification of training across Europe.

[399] See http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-medtech/

[400] Stratasys offers for instance compact printers to print dental surgical guides, such as the Objet30 (see http://www.additivemanufacturing.media/products/compact-3d-printer-for-dental-applications-)

[401] See similar trends at the sectorial level at http://www.tctmagazine.com/3D-printing-news/medical-3d-printing-report-estimates-value-of-industry-for-2/

[402] See http://www.materialise.com/press/3d-printing-the-future-of-personalized-healthcare-with-the-materialise-hospital-solution

[403] Opportunities for Additive Manufacturing in Surgical Planning and Modeling, August 2015, SmarTech Markets Publishing LLC

[404] Opportunities for Additive Manufacturing in Surgical Planning and Modeling, August 2015, SmarTech Markets Publishing LLC

[405] 3D opportunity in medical technology: additive manufacturing comes to life. Deloitte University Press, 2014.

[406] 3D opportunity in medical technology: additive manufacturing comes to life. Deloitte University Press, 2014.

2. Multidisciplinary collaboration opportunities should be stimulated at local, national, regional and EU level. As indicated, surgeons, radiologists and engineers are crucial for research and development with respect to healthcare applications. Bringing these parties together on project-level can initiate first and future collaborations.
3. Support to further **research and development** is required in order to overcome certain limitations at the level of the models themselves. In order to improve their accuracy and fidelity (for instance overcoming the simple geometrical reproduction and make possible the reproduction of surgery conditions, reactions and effects), R&D could be supported by all levels of government to further characterize the processes and materials at stake. R&D will certainly benefit from multidisciplinary collaboration.
4. Regional and national authorities could support the uptake of AM by hospitals by **co-investing** (providing subsidies) in the acquisition of printers. This co-investment could take many forms depending on the national/regional context but would allow lowing down the cost of AM printers made available to hospitals and surgeons.
5. There is still room for a broader uptake of AM in hospitals. This involves collaboration efforts at all levels.
    a. There is an opportunity to **strengthen the relations between healthcare professionals (surgeons), healthcare and AM providers** in order to facilitate the uptake of AM in hospitals. One of the prerequisite to such collaborations would be that they take place in a multi-disciplinary context. Collaborations could be set up through projects supported at the regional, national and European projects, which could range from collaborative to capacity building projects.
    b. Closely related to the above policy implication, is the need for **awareness raising**. One of the key challenges is here the one of streamlined information. This could be taken up by European authorities. In this respect, it is interesting to encourage networks and to identify pioneers and champions, which facilities the knowledge and information sharing.
    c. And there is the economic aspect which is also highly relevant for the hospital and patient; who pays for the cost of training and preoperative planning? There are quiet some differences across Europe. Does the individual itself pay for it, the individual's insurance or the national health provider? More clarity and uniformity at the national and European level would certainly benefit the uptake of AM in healthcare.

4.2.2 Plastic-based car interior components

4.2.2.1 Scoping

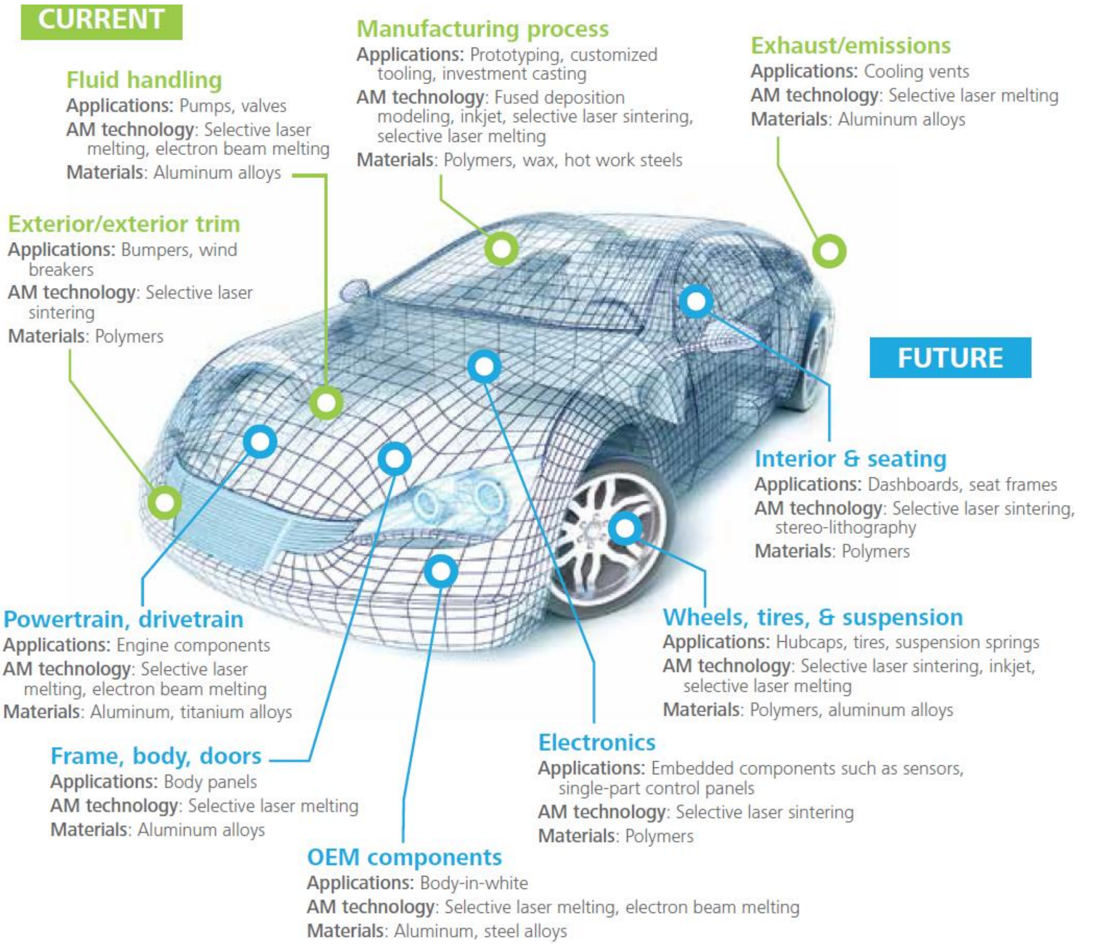
(i) Context

Additive Manufacturing could bring a revolution to the automotive industry[407]. 3D-printing in the automotive sector mainly came about in Europe by 2001 (Royal Academy of Engineering, 2013) and is now expected to reach a combined production volume associated to the generation of $1.1 billion revenue by 2019. The automotive industry already produces 100 000 prototype parts and molds with Additive Manufacturing according to a 2014 study by SmarTech Markets Publishing[408]. By 2019, the revenue generated by the sale of 3D-printers to the automotive industry should reach $586 million, while materials revenues would reach $376 million with a predominance of thermoplastics and photopolymers and an increasing use of sand molds to cast test parts such as for engines[409].Also metal additive manufacturing is being used by car manufacturers, to some extent for car exterior but essentially for demanding (and mainly engine) components and to a large extent to manufacture production tools[410] and reduce casting costs.

Giffi et Al. (2014) however note that the dominant trend in the automotive sector is still related to the exploration of additive manufacturing. Companies do not seek to take advantage of it for reasons related to limitations in scale (supply chain enabling) or scope (performance enhancement). Therefore, mutations in the dominant business models are not expected to happen soon as the use of AM is rather limited to prototyping and small series (few tens of thousands components).

[407] See http://www.autocar.co.uk/car-news/motor-shows-detroit-motor-show/how-3d-printing-could-revolutionise-car-industry
[408] See http://smartechpublishing.com/news/smartech-publishing-announces-automotive-industry-producing-record-volumes
[409] Source: http://smartechpublishing.com/news/smartech-publishing-announces-automotive-industry-producing-record-volumes
[410] Giffi et Al. (2014) explain that "*BMW, for example, has used AM in direct manufacturing to make the hand tools used in testing and assembly. These custom-designed hand tools have better ergonomic design and are 72 percent lighter than traditional hand tools. According to BMW, the customized tools helped save 58 percent in overall costs and reduce project time by 92 percent*".

Figure 45: Illustrative applications of AM in an automobile



Source: Giffi et Al., 2014

The automotive industry has been shifting from prototyping to an increasing use of additive manufacturing for +- production, experiencing now the production of tooling and other parts that frame the production process. It is seen as a pioneering sector in the field for which Additive Manufacturing can be applied to different aspects, ranging from specific engine or demanding components (gearboxes, etc.) to parts such as dashboards or car frames. Several key trends can be observed at sector level: "large print volumes for 3D-printed prototype parts", "design verification", and to some extent "the creation of functional parts used in test vehicles and engines"[411]. However, the use of additive manufacturing for production is still at an experimental stage in most companies, although in Europe some German car manufacturers are said to make use of additive technologies to a greater extent in their production processes.

Additive Manufacturing also led to the birth of new seeds of business models in the sector such as the one of Local Motors, an American company now active in Europe, that develops a business of "on demand" or "built-while-you-wait" car: according to its chief strategy officer Justin Fishkin, "improvements to the digital manufacturing process – using carbon-fiber-infused ABS plastic to build, in layers, the structure and bodywork of the vehicle – has cut the time needed to produce an entire car from 180 hours to just 44"; A first car produced by the company accounted for 50 main components for a total of about 80% of the carbon-fiber-reinforced plastic made reusable[412].

Box 33: The importance of customisation for the future of the car industry

In an interview to The Telegraph, Dick Elsy (chief executive of the High Value Manufacturing Catapult in the UK) stated that "*The next logical step for ALM is the premium auto sector (…) People are willing to pay for personalisation and at the moment that can only really be produced by handcrafting products. I can see people willing to pay a premium for that kind of personalisation in the £30,000 to £50,000 car range in two or three years.*"[413]

[411] Source : http://3dprint.com/72358/automotive-bn-dollar-market/
[412] Source: http://wardsauto.com/plants-production/your-car-built-you-while-you-wait
[413] Source : http://www.telegraph.co.uk/finance/newsbysector/industry/engineering/11455696/Why-3D-printing-is-set-to-revolutionise-manufacturing.html

By anticipation on future trends, some guesses are also formulated by different companies and information sources. For example, some sources depict the possibility of installing 3D-printers at dealerships. These printers could be used to print spare parts for cars. This would lead to a change in the value chain thanks to the suppression of warehouses dedicated to spare parts stocks[414] as these parts could be printed on site (one possibility would be for the dealerships to have printers dedicated to the printing of car parts). However, most of the assumptions remain to be proven in the near future, although some main developments seem to currently take place, such as in the field of environment-friendly car manufacturing. Particularly on the web, quite some communication took place regarding the second prototype of what could become the "greenest car in the world". This car named URBEE 2 follows the completion of the first 2013 prototype URBEE1. The team that manages its development plans that this car "*will have its entire exterior and interior 3D-printed*" (URBEE2 is currently looking for crowdfunding-based support; see http://korecologic.com/).

(ii) Application area: plastic-based car interior components

During the first phase of the study, the area entitled "*Personalized car interiors (e.g. dashboard) and exteriors (e.g. wing mirrors and other non-structural components)*" was selected. The choice to include this application area was based on the fact that it is a business-to-business area key to the competitiveness of the automotive sector with a broader outreach potential to other sectors such as aerospace but also machinery and tooling. It is usually associated to functional or non-functional parts, and especially to the design of the car: both interior and exterior parts are of importance because of their attractiveness and associated comfort that are key to attract consumers. An extensive web-based research led to the identification of a number of cases in which additive manufacturing has been used for printing car interior and exterior components. Most of the examples however prove to be more illustrative of what can technically be done with additive manufacturing to customize car interiors and exteriors, while limited information is available on the effective use of additive manufacturing by professional car interior and exterior manufacturers[415] (who are Original Equipment Manufacturers, or OEMs).

In order to delineate the scope of the application area, the main components of car interiors and exteriors were identified in order to allow for the identification of possible driving products. Car interiors and exteriors call upon different parts that are made of materials such as plastics[416] and various types of textiles but also (to a more limited extent) metal. They are subject to issues such as material and color choice, cutting, stitching and assembling[417]. Car interior and exterior components can be numerous and vary from one model to another (from speaker protections[418] to parts which design is left to the makers' community[419] for instance). It is however possible to flag commonalities between car products.

Car exteriors refer to the surface visible from outside the car and usually correspond to items such as lamp gards, sun shades, glasses and window visors, etc. (see for instance Figure 46)

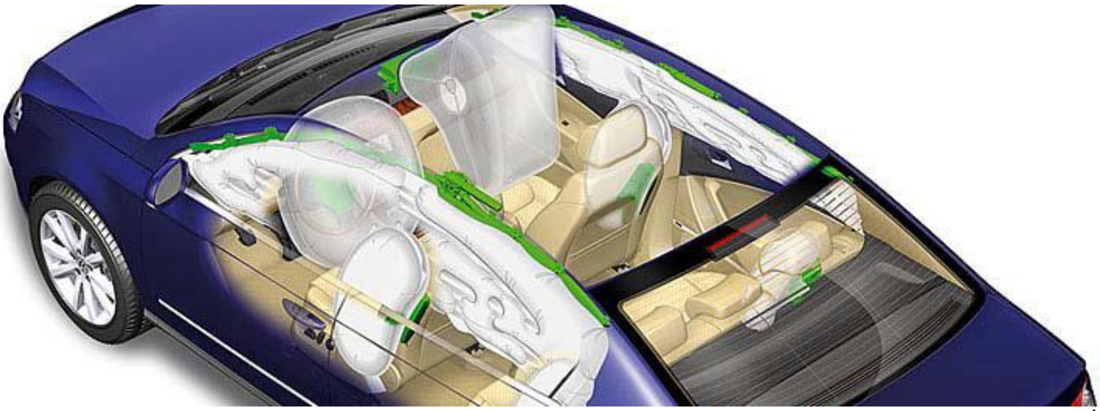
Figure 46: Body and Exterior of a typical vehicle (bumper, body panels and trims)

Source: Szeteiová (2010)

Car interiors on the other hand refer to the cockpit or cabin, including components such as interior carpets, rugs and floor kits and (dash) mats, upholstery (seats including cushions and chairs), headliners and floor liners, convertible tops and vinyl roof covers, as well as dashboards (see Figure 47). The number of parts in a cockpit can of course vary but usually accounts for about 250 parts with only 25 "*big*" parts, some of which are designed separately in order to allow for relevant testing. Among these parts, around 90 are directly visible to the customer.

[414] See for instance http://wardsauto.com/dealers/3d-printing-will-change-auto-industry-manufacturers-dealers?page=2
[415] Information was however gathered from different players such as car manufacturers themselves.
[416] See http://www.plastics.gl/automotive/styrenic-polymers-in-automotive-interior-and-exterior/
[417] See http://www.eca.be/en/eca-car-upholstery-11.htm
[418] See https://www.stratasysdirect.com/case-studies/automotive-personalization-brought-to-life/
[419] See http://www.3ders.org/articles/20150507-toyota-open-road-project-to-bring-3d-printing-to-custom-electric-vehicles.html

Figure 47: Interior of a typical vehicle



Source: Szeteiová (2010)

By extension, car interiors and exteriors can include car trims (items added to the interior and exterior of a car to increase its appeal) such as for interior vinyl, cloths, leather, wood grain, chrome or imitation leather upholstery, center caps as well as floor mats. For the exterior, a number of parts can be listed, including specific types of paint (pearlized for instance), add-ons (protective or decorative), plastic bumpers and pinstriping[420]. However, most of the car trims do not fall under the category either of car interior or car exterior component as they rather relate to decoration. Therefore, they relate to another type of market and will not be part of the analysis.

The approach selected in this case study is to emphasize the dominant products that are currently being 3D-printed or that will most likely be impacted by Additive Manufacturing in the near future. From the desk research and interviews, it became clear that the **plastic-based components of car interiors** are central while other types of components a rather marginal: non-plastic based components (such as carpets, textile parts of the seats, etc.) are not subject to Additive Manufacturing experiments or tests, and the cases of exterior parts (whether plastic-based or metal-based parts) produced with Additive Manufacturing are limited. Of course, some exceptions apply: one can for instance notice that titanium is sometimes used for car interior parts and in particular for the steering wheel. Nonetheless, these exceptions remain marginal in numbers. In addition, plastic is being increasingly used in car manufacturing and quite some emphasis is put on research on related production techniques. According to Szeteiová (2010), "*The average vehicle uses about 150 kg of plastics and plastic composites versus 1163 kg of iron and steel – currently it is moving around 10-15 % of total weight of the car (...) the plastics contents of commercial vehicles comprise about 50 % of all interior components, including safety subsystems, door and seat assemblies*". She adds that "*Although up to 13 different polymers may be used in a single car model, just three types of plastics make up some 66 % of the total plastics used in a car: polypropylene (32 %), polyurethane (17 %) and PVC (16 %)*".

Although only visible parts are most likely to be subject to increased customization, Additive Manufacturing is used for both visible and non-visible interior parts. However, the use of Additive Manufacturing remains focused on prototyping. One can find examples of 3D-printed car interiors such as the Pininfarina Sintesi Concept Car[421] or the Peugeot Fractal (see Box 34) prototyped in partnership with Materialise.

[420] See http://www.ebay.com/gds/What-Is-Car-Trim-/10000000177635226/g.html
[421] See http://manufacturing.materialise.com/proven-solutions-automotive-industry

Box 34: Peugeot FRACTAL

The Peugeot Fractal is a concept car that was designed as an urban electrical vehicle in cooperation with Materialise. 82% of its interior components were produced with additive manufacturing, such as window frames and other surface part (such as the car floor, parts under the dashboard, etc.) but also some exterior elements as well. These are mainly related to the acoustic of the vehicle and include for instance components between the wheel and the cabin that were designed to buffer the sounds coming from the road. Here, white anechoic components were printed with polymer, powder bed fusion was mobilized. The steering wheel was 3D-Printed with aluminum powder in order to get a lighter wheel (with a specific form) with an empty inside which complex form could only be allowed by Additive Manufacturing. The use of plastic-based parts produced with Additive Manufacturing was particularly relevant to the complexity of i-Cockpit® given the complexity of its ergonomics that even gave the name to the Fractal. Fine and efficient but also lighter design was achieved through the 3D-printing of the cockpit that required particular forms[422].

Source: http://www.peugeot.com/en/news/fractal-amplifies-the-peugeot-i-cockpit-with-sound

4.2.2.2 Identifying value chain components

(i) Identification of key players and usage of Additive Manufacturing

Although they are facing strong competition from their American counterparts (see Box 35), a number of European companies currently make use of additive manufacturing to design car interior components. A key example was showcased by Materialise in 2008 that used the additive technology Stereolithography in the context of the Pininfarina Sintesi Concept Car project in order to design key components such as "*the radiator, control panels, roof antenna, remote controller, roof light cover and most importantly, the instrument panel*" seen as "*the centrepiece of the car's interior*". All the interior of the car (also called the cabin) was conceived as an integrated element, part of the overall design of the car. On its website the company reports the following: "*The instrument panel is designed as one integrated semitransparent piece (…) The eventual panel was "printed" in its full width on a Materialise Mammoth stereolithography machine, with a build volume up to 2150 x 700 x 800 mm, in a translucent PP-like epoxy (Poly 1500). Due to its complexity, also the radiator had to be manufactured by means of additive technologies. The production of the smaller components like the roof antenna and remote controller show the endless personalisation possibilities of additive manufacturing.*"[423] Other cases are presented by the company, such as collaborations with auto manufacturers such as Jaguar (printing the cabin interior of the CX-75 Concept Car with Fused Deposition Modelling and stereolithography[424]) or Audi (printing parts with photopolimeryzation[425]). One of the car interior cases is a cooperation of Materialise and Mercedes in collaboration with Classictacho GmbH, in the context of which the interior of the Classic Sports Car 300 SL was restored using Additive Manufacturing with a particular emphasis on the instrument panel backlights: "*The new version of the backlight consists of a bottom section in laser sintered polyamide with a black finish and vacuum casted light points in transparent HMPU13. Separate inner tubes guide the light into the right direction, combining ambient light for water and oil temperature, fuel level, oil pressure and a cluster of pilot lights including the specially formed pilot light for high beam*"[426].

Box 35: The strong presence of US-based players in car interior Additive Manufacturing

When identifying key players involved in the additive production of car interior components, the dominance of US players could be observed. The strong position of US players is in particular visible when considering the large presence of several specialized companies in the US such as AI Design[427] (with a dedicated line on car design, including upholstery and interior trim) or larger companies such as Stratasys (see for instance the collaboration with Equus Automotive on the BASS770 car interior[428]). Stratasys used "*Direct Manufacturing's Stereolithography (SL), Fused Deposition Modeling (FDM®), Laser Sintering (LS) and cast urethanes (…) to build multiple interior and exterior components including the instrument panel, headlight and taillight bezels, HVAC ducting, glass trim panel fender, console covers, seat belt covers, under hood components, and more*"[429].

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422 See http://www.peugeot.co.uk/concept-cars-showroom/fractal/concept-car/
423 Source: http://www.materialise.com/cases/materialise-contributes-to-pininfarina-sintesi-concept-car
424 See http://manufacturing.materialise.com/cases/materialise-helps-jaguar-engineers-realise-cx-75-concept-car
425 See http://www.sculpteo.com/blog/2012/04/04/3d-printing-for-the-car-industry-the-audi-example/
426 See http://manufacturing.materialise.com/cases/bringing-back-spirit-classic-sports-car
427 See http://www.aidesign.com/contact and http://3dprint.com/9675/3d-print-luxury-car-parts/
428 Depicted on https://www.stratasysdirect.com/case-studies/new-american-muscle-car/
429 Source: https://www.stratasysdirect.com/case-studies/new-american-muscle-car/

However, the use of additive manufacturing remains focused on prototyping or the production of low volumes. Most interviewees assume that all main car manufacturers are involved in additive manufacturing, although to a variable extent. Car interior also reaches out to specialised companies and projects with potential spill-overs to the regular car manufacturing processes (see Box 36). In the development of the Bloodhound project, the UK-based engineering company Cambridge Design Partnership developed a 3D-printed wheel for the "world's fastest car" to exceed 1.000 miles per hour. In such conditions, precision in ergonomics is seen as crucial, such as when positioning buttons on the wheel while taking into account the speed effects on the drivers' thumbs position. Here AM proved highly efficient for the production of initial prototype parts and make the wheel as light as possible following a biomimicry approach: the use of additive manufacturing was however focused on the production of the test parts, while titanium was preferred for the AM of the final steering wheel.

Box 36: From road to race

The higher performance and customization of cars is even relevant to Formula 1 where Dash CAE managed to cut lead times by 83% (Stratasys, 2008)[430]. In this particular field, one can mainly find Stereolithography (SLA) and Selective Laser Sintering (SLS) such as depicted by Additive Manufacturing Automotive (2015) in order to gain circa 30% weight compared to traditional manufacturing: "*Many components are now 3D-printed, including the trim around the switch panel on the steering wheel, floor sections and front wing parts. Roll hoops are printed, as are front flap hinges and adjusters. Rear tyre decks and lower leading edges of the side pods; Kiel probes and brake ducts. All have been produced by additive manufacturing processes and raced by F1 teams in the past*". Here, customization is said to be relevant as parts can be printed for different racing circuits (for which different performance patterns will be expected from the racing cars) as well as the development of mobile printers to be used during the races, for instance to replace parts or adjust the car performance. In that respect, Graham Tromans, Principal and President of AM consultancy GP Tromans Associates explained to The Royal Academy of Engineering (2013) that "*engineers are using AM to manufacture parts in a highly reactive way. "They can now analyse the car's performance while it goes round the circuit and have a new part getting ready before it finishes the race*".

The "*gate keeper*" approach proved to be fruitful, but using it, we also encountered some limitations: the strategic value of the information sought led several contacts in the main car interior and exterior industry to decline our invitations to discuss, due to the too strategic value of the information requested.
In addition, a certain fatigue was expressed by corporate and technical contact points in the companies who are dealing with a number of similar enquiries linked to European but also national studies on Additive Manufacturing.

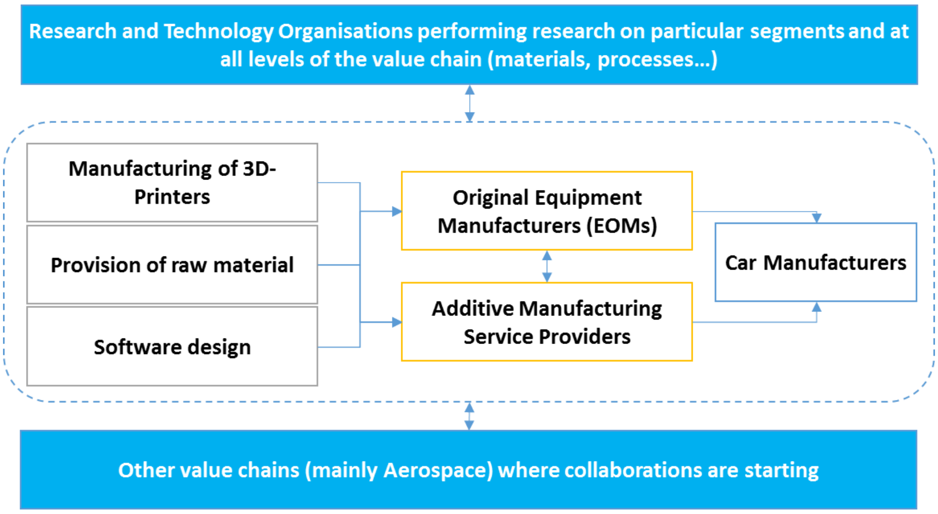
(ii) Composition of the value chain

In order to better understand the status of additive manufacturing in the car interiors' industry, the value chain is reconstructed in order to position the key actors who are active in Europe but also (to a more limited extent) outside Europe[431]. Most actors involved in the additive manufacturing of car interior components are mainly located in Germany. Key players are also located in France, Italy, Spain, Sweden, Belgium and the United Kingdom. A more detailed list of players identified is available in Section (iii).

Figure 48 illustrates the main components of the generic car interiors' value chain seen through an additive manufacturing perspective. This value chain is somehow similar to the classical one, except for the introduction of new players which are mainly companies specializing in additive manufacturing, some of them being specialised in the mechanical sector, others being active in a broader range of areas. In order to make the involvement of key players clear along this value chain, Figure 63 provides more detailed examples on which segment(s) particular organisations are active.

[430] The company would mainly call upon SLS and FDM
[431] Worldwide competition in this area, from Japan and the US in particular, is very strong.

Figure 48: Main segments of the car interior additive manufacturing value chain



Manufacturing of 3D-Printers
On top of the value chain are the software and materials providers, and the 3D-printer providers such as EOS (DE), ConceptLaser (DE), RICO (US and HP (US). EOS provides for instance car manufacturers and related groups such as PSA and Renault in France or BMW and Volkswagen in Germany. A large number of German companies are active in this segment, including for instance Oxojet, and SLM Solutions[432]. Non-EU players are 3D Systems (US), Stratasys (IL), InJet (US), Matsuura and SOUP (JP)

Provision of raw material
The materials are provided by companies that are specialised in different areas. In the field of car interiors, this entails metal powders (provided by companies such as LPW) and resins and plastics (provided by companies such as DSM). Although the companies providing metal powders are part of a global and highly fragmented market, the plastic market under the scope of this case study appears to be more condensed with the involvement of European players such as DSM (in particular the DSM branch called SOMOS), EVONIK and ARKEMA. The nature of the materials is a key determinant of the value chain: historically, metal additive manufacturing is related to different chains compared to plastic or ceramic AM.

Software design
Software companies are central providers on the market, which is structured around dominant players including Dassault, Siemens PLM, Autodesk and Materialise in the mechanical field. The players at this level of the value chain are usually traditional CAD software companies that expanded to Additive Manufacturing as a natural extension of their activities. The Solidworks (Dassault) software appears to be widely used in the sector together with Protoshop (Protoshop). These software packets have the particularity of being generic and therefore apply to a broad range of sectors (including aerospace). They allow for scans but also design from scratch and usually include interfaces with 3D scanners and relevant navigation possibilities that allow viewing, sculpting, etc. The drivers of the 3D-printers are integrated into these softwares that can read standard Windows drivers and remain compatible to all 3D-printers according to existing standards (for instance under Windows 8.1). To some extent, 3D scan companies should also be mentioned here as they are also active at this level of the value chain, making for instance use of Polyworks[433] (see for instance 3DScannersUK) to sort out scans that will be further refined via CAD and then printed by the relevant players (service providers, OEMs, etc.).

Original Equipment Manufacturers (OEMs)
The Original Equipment Manufacturers (OEMs) who are historically the main providers of car manufacturers include among others Tenecco, Boysen, Faurecia, Edag, Eberspaecher, IAC, Johnson Controls Inc., YANFENG and Valeo. The players active in Europe are international companies which headquarters are usually located in Europe, America or Japan. EU companies can rely on a very good technology base to create production systems. However, the design concepts seem to be missing for Additive Manufacturing to develop further than the current state of prototyping.

[432] And for information, for non-plastic components mainly ConceptLaser and Trumpf.
[433] See http://www.innovmetric.com/

Additive Manufacturing Service Providers.

At a similar level to OEMs, are Additive Manufacturing service providers, of which Materialise (BE) figures as the central player in Europe, although facing competition from American companies (3D Systems and Stratasys) and other companies (Dash CAE [which printed a diffuser floor in black ABSplus™ for Tesla][434] or 3Dscannersuk in the United Kingdom for instance) which can be small players (some of them following a high-growth curve) but also large players (Local Motors, an American-based company, is for instance increasing its presence on the European market. Prototyping companies are active on this segment such as Ogle Models Prototypes and smaller companies which an interviewee says are "*about 200 just in Germany using Additive Manufacturing*". The 3D-printing service providers cooperate with EOMs but also directly with car manufacturers who eventually integrate all components and parts into a final product.

Car Manufacturers

The car manufacturers include BMW, Koenigsegg, Peugeot, Renault, Volkswagen, Audi, Porsche, Daimler, KIA, Lamborghini, Ferrari, Fiat, Volvo, Maserati and their American and Japanese counterparts (Ford, Honda and in particular on additive manufacturing General Motors). They make use of additive manufacturing to prototype car interior parts. The use of AM by car manufacturers concerns specific aspects of the manufacturing process:

- Some make use of the technology for tooling (for instance fixtures and assembly lines)
- Most of them make use of additive manufacturing for prototyping
- Some isolated cases of small series production were evoked by interviewees who did not provide more details on the components concerned.

One of the interviewees in charge of car interior for an important European manufacturer explains that Additive Manufacturing is used for verification purposes. Here, only pre-verification and end verification is under scope. Particular parts are concerned (fixtures, packaging, etc.) but also assembly verifications. Additive Manufacturing remains focused on the early phases in that specific case: the company owns its own printers and scanners and prototypes plastic components for car interiors such as dashboards etc. Another use concerns the non- or late delivery of specific components by suppliers which would sometimes justify the use of additive manufacturing for the production of specific parts. No research is done on the possibility to use additive manufacturing for production purposes. The externalisation is therefore rare and collaboration happens here mainly with the usual engineering service companies the car manufacturer is used to work with in the same region and only for test part production. However, collaborations are observed between a number of car manufacturers and service providers such as Materialise, FKM or Layerwise. These partners are usually mobilized for complex design and manufacturing, especially for small series production. Many collaboration cases are observed that involve European car manufacturers and American Additive Manufacturing service providers, such as the case of Renault collaboration with LocalMotors[435], or Koenigsegg that teamed up with Stratasys (see Stratasys, 2013).

Research and Technology Organisations

Also several collaboration agreements with RTOs can be identified in the area of additive manufacturing of car interior components. Among these, Fraunhofer, Aachen University, the University of Düsseldorf, the University of Hamburg, are involved in government-funded projects in Germany. Some are clearly in a lead position in Europe, such as Fraunhofer or the Laser Zentrum Hannover as they collaborate a lot with the private sector on strategic research. A new cluster in Milan (Italy) is currently investigating issues of additive manufacturing in the car industry, and other Italian research centers seem to be involved in this field located in Milan, Bologna, Salerno, and Padua. Among the topics investigated, the most popular seem to touch upon mechanical properties, processes, materials and productivity issues.

[434] Source: Stratasys, 2008

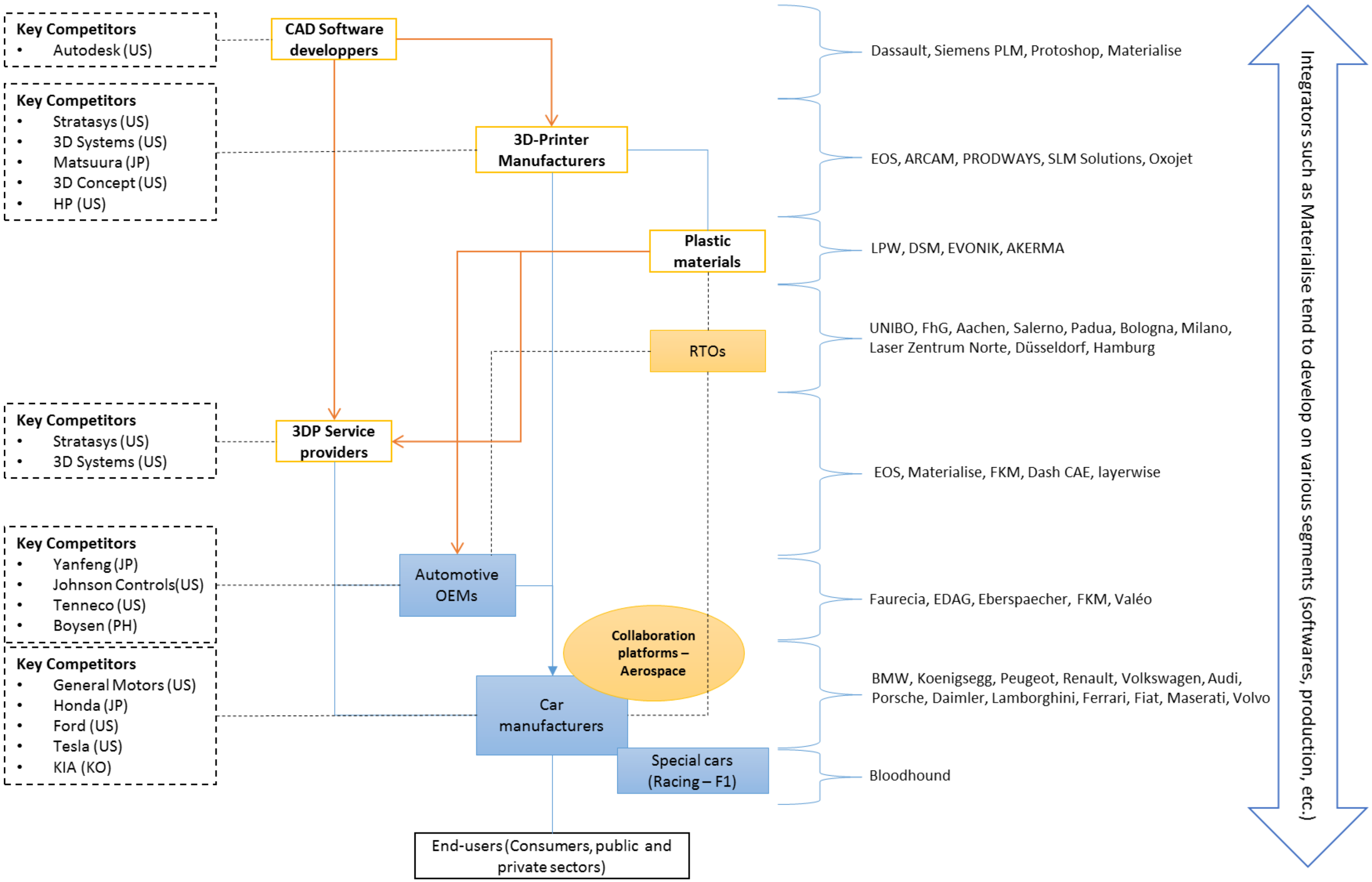
[435] See https://localmotors.com/LM-Kate/renault-on-twizys-powertrain-in-3d-printed-car-at-imts-2014/ and http://www.usine-digitale.fr/editorial/open-source-impression-3d-renault-explore-de-nouvelles-voies-pour-innover.N303903

Connections with other value chains

Another dimension is the existence of cross-value chain cooperation: although no name was mentioned, several interviewees referred to collaboration platforms being set up between automotive and aerospace companies willing to develop additive manufacturing on common topics such as materials and productivity issues. An interviewee referred to Lamborghini for instance that would source technologies from the aerospace sector as both sectors would answer to strict standards. Other collaboration opportunities exist at the level of this value chain and relate to other transportation sectors.

From an international perspective, the markets seem to be evolving relatively slowly at this moment, although Asia (and China in particular) presents signs of being a growing market with relevant potential for suppliers such as Faurecia (2015) which is also quite well positioned in the United States. AM does not yet show any disruptive effect in the value chain as it is currently used for rapid prototyping purposes mainly. Similarly, AM has not (yet) changed the competitive position of the players at stake, although new players are entering the car industry such as new service and machine providers. In addition, an interviewee referred to different acquisitions that are taking place such as Alfaform (acquired by Protolabs), Netfob (bought by Autodesk) and FIT (in which Autodesk recently invested) in Germany, but also Layerwise (acquired by 3D Systems) in Belgium and a number of others (ExOne, etc.). Large American Additive Manufacturing companies are investing in the European markets through acquisitions and the mobilisation of capital in key EU companies. AM remains to reach production, and the feedback received from car manufacturers along the process confirms that there is a long way to go as technological and cultural barriers still hamper the further uptake of AM in the sector.

Figure 49: Illustration of the car interior additive manufacturing value chain



Source: IDEA Consult, 2016

Note: the names of the organisations mentioned are only included for illustration purposes and no colour code was applied – colours codes were only added to make the figure more readable.

(iii) Functioning of the value chain and critical factors

The most important critical factors driving the value chain are the issues of efficiency and productivity: the costs and speed of additive manufacturing are hampering its uptake and further deployment as the speed remains too slow compared to more classical forms of manufacturing, and the costs of producing with Additive Manufacturing are too high to replace traditional manufacturing techniques. Also, the quality of the parts produced (especially in terms of surface) are not yet reaching the current quality standards and the size limitations of 3D-Printers play a role in limiting the ambitions of Additive Manufacturing production of car interior parts.

Standardization is a key issue in the automotive industry. This is seen as one of the main critical factors impacting the implementation of AM although it has to be noted that car interior components are less subject to strict requirements applying to structural parts. In addition, the testing of mechanical properties as well as the availability of relevant materials for series application are also to be listed as critical factors.

The bargaining power of players active along the car interior value chain is deemed balanced by the interviewees. No clear gap in European capabilities could be noticed except to some extent at the software level where some claim that more specialised development and the integration between CAD softwares could be foreseen. All capabilities are present in Europe, from materials and software design to the manufacturing of components and their assembly into the final product. However, the capabilities are not equally distributed over the European territory and are mainly concentrated in Western European countries such as Germany, Sweden, France, and the UK.

Several competitiveness issues can be highlighted at this stage. For instance, Europe is currently facing a strategy of buy-out by large American companies (including Autodesk, Protolabs, Stratasys, and 3Dsystems). Through their mergers and acquisitions, these large players are getting an important share of the European market thanks to an important amount of capital associated to investors from the Silicon Valley.

Organizational culture and skills are seen as key barriers to the adoption and deployment of AM in the present value chain. Moreover, incentives to change are sometimes missing: the current 3D-printing developers are for instance benefitting from a less competitive market and were said by some interviewees to "enjoy" sufficient turnover with prototyping. Therefore, these players are less urged to foster the development of AM towards the next production level.

Regarding future applications, first insights are provided by the interviewees regarding bio-mimicking and the renewal of process manufacturing paradigms. The integration of multiple components such as in the URBEE case is of main interest to many players as it could save time (and therefore money) regarding the current assembly process. The potential of the car interior value chain lies in the development of components that can be produced with AM, while at this point of time AM is mainly used for prototyping purposes. The development of complex interior parts and customized parts is of particular interest, and is most likely to be associated with higher economic value. But at this point of time, looking forward to new developments of the car interior value chain would be speculative as the next logical phase either lies in the scaling up of AM performance or in the anchoring of AM as a tool dedicated to prototyping or tooling. In both case, AM brings new dimensions to relevant components (in terms of complexity and technical properties).

4.2.2.3 Missing capabilities

(i) Regional dimension and missing capabilities

Looking at the regional dimension of the case study "personalized car interiors and exteriors", one can notice that the existing capabilities are concentrated in Western European countries and few links can be observed between the players at stake or the regions from which they operate, except of the current Vanguard Initiative that focuses particularly on 3D-printing.

- Companies like Materialise is mainly operating from Belgium (Flanders), but also has offices in Germany. Also Layerwise (now 3DS) operates in Flanders, Belgium, while SIRRIS operates from Wallonia.
- In France, companies like Initial (Gorgé) in Rhône Alpes as well as Shapeways (Gorgé) and PSA in the Paris region, and Phenix Systems (now 3DS) in Auvergne. The PEP cluster (working in close collaboration with Renault on the topic of AM) is also spotted.
- In Italy, the main region concerned with AM capability development are Piemonte and Lombardy. Other regions that house car manufacturers like Ferrari or Lamborghini (Emilia Romagna) and also companies like Beam-IT (Emilia Romagna) are also in the process of developing AM competences.
- In Spain, the main activities are located in Catalonia (where ASERM is located).

- Germany is the country where most AM capabilities could be identified as the main printer manufacturers such as SLM-Solutions (Schleswig-Holstein), EOS and ConceptLaser (Bavaria), but also Fraunhofer (Bavaria, Hesse), LZN (Hamburg - Low Saxony) and other players in Baden Wurttemberg could be identified. Also other key suppliers such as EDAG (Hesse) are located in these regions. Even the French OEM Faurecia is developing its AM capabilities in Germany.
- Also Sweden is developing relevant capabilities with Koenigsegg (Ängelholm) and Volvo (Västergötland and Bohuslän).
- The main providers of raw materials are also located in Western Europe, with LPW (UK) and DSM (NL). One should note that main printer providers also provide their own materials (for instance powder bed system providers), often according to a locked-in system strategy

From a geographical repartition point of view and when focussing on specific AM capabilities, it is possible to observe a level of concentration in specific regions, mainly (though not only) in German regions. Based on the desk research and interviews performed, it was not possible to identify key players in the Eastern part of Europe. AM capabilities are indeed mainly concentrated in Western European regions. In addition, one should note that due to the strategic nature of AM as a technology, companies are reluctant to communicate the precise location of the sites where they effectively develop capabilities with regard to AM. Further refinement of the regional dimension will be pursued in the second phase of the case study process. No main capability appears to be missing, though the United States is mainly leading the field of plastic AM systems.

(ii) Barriers to the uptake and further deployment of AM in the value chain

The main characteristic of automotive AM is that it is limited to tooling, prototyping and low-volume series production. In that context, Cotteleer et Al. (2014) identified barriers to AM in the automotive sector. The first barrier presented by the authors relates to the availability of relevant materials. Research is in that regard being conducted on this topic in the context of FP projects but also national R&D schemes dealing with graphene, thermoplastics, or advanced materials in general. As a second barrier, Cotteleer et Al. pointed to post-processing and product quality. Finishing is still key to having neat 3D-printed components. The authors recommended to foster qualification and standardization of relevant machines in that respect. They also pointed to other challenges such the manufacturing of large parts, talent shortage and IPR concerns. All these barriers are to some extent found in other sectors where AM requires further technological development in order to compete with traditional technologies.

In the process of conducting this case study, more precise barriers could be identified that apply to car interior components. One of them echoes broader needs to consolidate the use of AM in the automotive industry: the **need for further qualification and standardization of the materials and processes at stake.** Among other aspects these are crucial to the consistency of production outputs (in terms of quality and properties) across the world. Others were more specific to the value chain under the scope. These barriers differ to some extent from the ones that are flagged by Cotteleer et Al. (2014) but echoe some obstacles identified by the authors such as post-processing and finishing issues or parts' size limitation. The key barriers to AM adoption and deployment in the plastic-based car interior components' value chain were clustered into two main groups.

Technology performance and productivity

Economies of scale in the automotive industry are based on the production of large volumes. Considering this main parameter, one can understand that AM parts' quality and related technical possibilities are not yet the best available on the market when compared to current –traditional– technologies. Printed parts are not produced fast enough, are still too costly and not of an enough good quality to compete with traditional production methods.

- The time and cost dimensions are key to the car interior components value chain. So far the two dimensions make AM not the best solution for producing automotive components:
  - The **production rate** of car interior components is far beyond the reach of current AM systems. These are therefore used either for small series production – but no clear example could be gathered to illustrate the type and the numbers of units of components produced in short series in that context - or in case[436] of luxury car makers as Bentley, whihc for example, used its in-house AM capabilities to customize the dashboard in a case where manual modification would have been time consuming
  - The existing technologies also reached a high level of efficiency; the scale effect leads to cheaper **costs** when the production numbers rise. This is not the case with AM where each and every end product costs the same price than the previous one. In addition, the use of AM remains costly compares to other technologies.
- Some technical limitations can be flagged.

[436] See Phil Reeves (2012), "*Putting 3D-printing into your value stream: Opportunities for new business models*," Econolyst presentation, Printshow London 2012, October 19, 2012 quoted in http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-automotive/#end-notes

- The level of **surface finishing** is problematic as it usually requires post-processing. The **quality of the end parts is therefore not sufficiently good** when these are produced with AM. This is an important issue as AM as such does not yet provide on its own parts with good surface finishing which implies that each printed part would require post-processing (and associated costs) to reach an end stage. When considering car interior components, this is an important factor as the surface is what car users are in direct contact with.
- The maximum **size of the printed parts** is too limitative: current systems do not allow printing parts that are large enough (such as a fully integrated dashboard). With current systems assembly is still needed for 3D-printed car interior components. Size is therefore a critical barrier to the further use of AM to print car interior components. Several interviewees pointed at this issue especially from the point of view of the understanding of mechanical stress in AM, but also from the point of view of the material properties (AM components are said to be less strong than the ones produced with injection molding for instance).
- Also the **durability/sustainability** of the parts produced with AM is not optimal yet. When coming to car interior components, a certain resistance should be observed to certain temperatures but also to vibrations to allow some levels of acoustic. That remains a challenge.
- In addition, an interviewee put forward a question mark on the **possibility to effectively automate** AM in the production process such as done for other technologies.
- Finally, one should note that the design rules for designing cast parts are not the same than the one to design 3D-printed products. The **lack of clear and appropriate AM design rules** was therefore pointed by several interviewees as one of the factors slowing down the adoption and deployment of AM, for instance across the engineering community.
- Although the capability is not missing as such, it should be improved: **design capabilities** and in particular **engineering software** should be strengthened and improved.

Business factors

Some of the barriers do not relate to the current level of AM technological performance. These relate to business-specific factors such as under-investments and human resources.

- Human resources are key to AM uptake and deployment. The issue of AM skills was flagged by several interviewees as curricula should be updated to include AM in engineering and design tracks. The **lack of skilled workforce** has been pointed as a main weakness of the European players along this value chain.
- **IPR** concerns were raised at the level of the designs, who some industry players fear they could be stolen and reproduced by competition. This barrier is not about the rights associated to the designer(s), but rather the copyrights of the CAD file(s). The possibility to hack and reproduce AM designs of particular tools or final parts and components could be a danger according to some interviewees. It is also foreseen that the possibility to purely scan and reproduce a part would allow competition be able to reproduce technological advances and would therefore negatively impact competition in the field. This barrier leads both technical and management resources in large organisations to a fear of losing a competitive advantage because of the availability of a technology that allows easy scan-based reproduction of parts and products. There is in addition a fear that AM would foster the 'free rider' effect where private entities would wait for innovation costs to be bore by others, slowing down technical and economic progresses.
- **Risk aversion** in the EU industry – and not only related to the automotive sector - was pointed as another barrier leading to under-investment in AM. Interviewees pointed at the strength of the European knowledge basis, while observing a **lack of investments** in the development of AM compared to the United States where higher levels of investment and financial support are brought by the private sector.
- AM printer manufacturers and service providers are **not incentivized to innovate**. The sector is growing at a fast rate and current prototyping activities generate a sufficient level of turnover for the European suppliers who are not constrained to invest in order to move to new activity segments or develop new solutions and find new uses.
- A both **cultural and paradigmatic barrier** should be highlighted. This barrier consists in **conservatism**. Some interviewees referred to this as a too anchored and sclerosed way of thinking the production process in many factories. There is a need for rethinking production processes as to better take advantage of the possibilities offered by AM. This even translates in some of these large companies into an organisational issues: several interviewees referred indeed to the fact that AM is not integrated in the production chain and is even isolated as a topic investigated by one or more specific units with little links and spill-overs to other units.

- It particularly (but not only) came out as a main lesson from an interview with Jim Kor, CEO of Kor Ecologic and a leading Canadian innovator at the origin of the URBEE cars[437]. Paradigmatic changes should be operated at the level of the design of AM-based products for which design rules should be made clear. As an example, the interviewee referred to the idea of plastic-based fuel tanks which were expected to be too expensive and proved not to be after testing. A similar example was used by the interviewee to explain that although lead times might seem longer, AM could allow the suppression of tooling steps along the process[438]. Another interviewee referred to large corporations where human resources leading series production activities would be culturally reluctant to the adoption of AM. The **cultural** and **paradigmatic** aspects are not to under-estimate: several interviewees pointed to these aspects as one of the main barriers to the further deployment of AM along the present value chain.

4.2.2.4 Conclusion: opportunities for public support

The automotive industry is seen as a pioneer in the field of AM. Lead users such as Ford Motor adopted the technology in the 1980s and still use it. However, its uses of AM have mainly been limited to prototyping and tooling[439]. AM in this area is very dependent on cost and scale but is also constrained by other factors such as certification. When considering non-structural components however, certification does not play a crucial role; economic factors do. When considering the interior of the car, most of the AM components are made of plastics. The related technology and materials are therefore quite different from metal ones. The impact of AM on the value chain of these components did not (yet) imply any ground-breaking change in the configuration of the game. It however led to the slow emergence of new business models (such as the one of LocalMotors) and new players to be involved in a quite concentrated setting where OEMs and integrators are large multinational firms. Although the use of AM in the automotive industry did not evolve fast over the past decades, new trends can be observed that might impact the uptake of AM by the industry: new brands are growing on the market such as Tesla, Google, etc. who are perceived as a possible threat by some interviewees. Such structural changes might affect the composition of the value chain and could possibly lead to technological evolutions. Other trends can be observed:

- The use of AM is currently driven by the issues of time, costs and scale. In the field of AM it is therefore mainly oriented towards the **printing of lightweight and/or complex parts**.
- In the field of car interior components, both metal (to print driving wheels for instance) and plastics are being used. Plastics remains the dominant type of materials as it is being used to produce parts such as dashboards or window frames. However, one has to note that despite of the strength of a few Western European companies, the market of plastic printing systems is mainly dominated by non-European based players such as 3DS (US) and Stratasys (formerly US and Israel since 2012) . The further exploration of **composite material**s and development of these is however seen as an important development track because European players hold a good position on composites.
- New perspectives are being drawn with the development of **hybrid printing methods**. These could enable new possibilities of having better quality products with the integration of additive and subtractive techniques.
- Another development track that is being explored by the industry is the one of **multi-material and multi-colour printing**[440] that would allow for better component integration and the possibility of printing lighter parts.
- **Mass customization** is still an emerging niche. Car interior components are showing strong potential in that respect as they are not subject to the same certification constraints than structural components. Moreover, personalisation could be brought to different parts but the integration of such process into the production and distribution chain remains an open question.
  - In the end of the line one could expect to see the **full printing of customized cars**. Despite of the certification constraints, this trend is effectively emerging with the lead example of LocalMotors (who collaborates with European players such as Airbus) in the United States.
  - URBEE 2 shows the possibilities offered by AM in the context of car 3D-printing.

Policy implications could be derived from the analysis of the value chain and the trends and barriers it currently faces. The most fundamental barrier to the use of AM for the production of plastic car interior components such as seat frames or dashboards is clearly the one of performance. Currently available systems do not perform fast enough and cannot at this point of time compete with traditional manufacturing methods and their associated production costs. The main and top priority track for AM in this field is therefore the one of technology development.

[437] See https://korecologic.com/about/team-2/

[438] The integration of multiple parts into a sole component could lead to a reduction of the number of molds to be used as well as other associated items (including the associated steps in the manufacturing process)

[439] To some extent, the manufacturing of short series was evoked by some interviewees who did not provide any concrete example of parts or components effectively produced with AM.

[440] The US-based firm Stratasys recently launched its Stratasys J750 in that respect – see http://www.stratasys.com/j750

No production stage will be reached by AM unless the performance of the technology is improved or a new type of use is found.

1. Therefore, further R&D should be conducted in order to bridge the current state of AM uses and AM-driven production opportunities. R&D support could be brought at all levels of government, from Regional to European levels (including the national level). Supporting R&D in the area should aim at:
    a. Strengthening the **qualification** of materials and processes mobilized in AM-oriented manufacturing to improve its performance and the quality of printed items;
    b. Developing the **size possibilities** offered by AM systems but also the further application of biomimicry concepts to production in order to optimize the parts produced;
    c. Supporting the development of **hybrid manufacturing** methods combining subtractive and additive methods to allow for greater part integration potential and improved quality of the end products;
    d. Supporting research and development on the AM of **composite materials**;
    e. Further support parts **optimization** and **integration**;
    f. **Multi-material and multi-colour printing** is another track to be followed;
    g. **Software** engineering **and design capabilities** should be **strengthened** in order for the systems developed to gain in stability when designing 3DP products.
2. Under-investment in AM calls for **co-investment from governments** whether they are regional, national or European public entities. Risk sharing should therefore be buffered in order for companies to invest more easily in risk-associated projects. This could for instance be done through voucher schemes or collaborative R&D co-funding.
3. **Awareness should be raised** in the private sector in order to provide company managers and other resources such as engineers with relevant information about the possible benefits offered by existing AM systems. The European Commission is most likely to be the best to streamline such effort of information diffusion. This could for instance take the shape of a website developed by the European Commission but also appropriate events dedicated to AM in the area under the scope.
4. AM system and service providers are not incentivized to innovate. **Demand could be stimulated** in order to trigger further technological development in the industry. For example in some other industries, the impact of environmental regulations leads to an increased demand for more efficient systems, impacting by then the development goals of sub-system providers and integrators. Demand can therefore drive strong changes in the industry.
5. A possibility would for instance be to strengthen the information capabilities of key **Intellectual Property** instances (by setting up an observatory that could be related to the EPO and/or IPO for example) in order to watch over new industrial designs and their reproduction.
6. **Skills** should be developed to allow European workforce to better integrate the use of AM in a productive way. **Curricula** should be updated and developed in that respect, which can be done at the regional and national levels under the coordination role of the European Commission. A consultative process could take place in order to set the stage.

4.2.3 Metallic structural parts for airplane

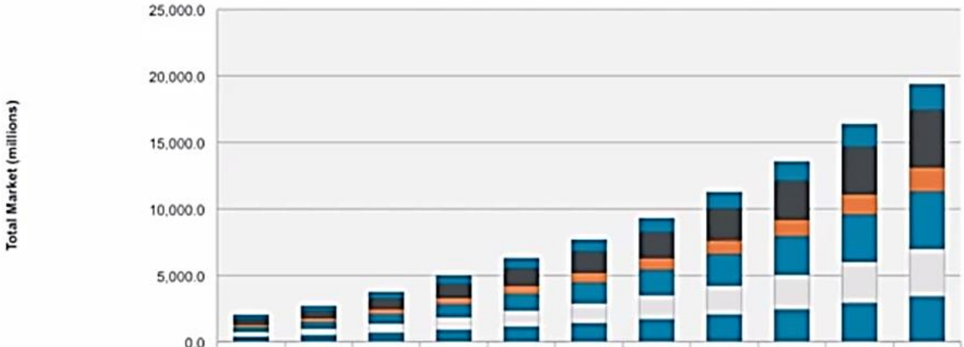
4.2.3.1 Scoping

(i) Context

Both the **aerospace and automotive** industry are currently dealing with additive manufacturing and are considered pioneering industries in that respect[441]. As Figure 1 shows, both aerospace and automotive AM are expected to grow in the coming 7 years. Companies in both sectors make use of AM to achieve optimization of specific parts. One example is the engineering company EDAG which recently produced a bionically inspired body structure, the 'EDAG Light Cocoon'[442], as a concept car exhibited in the Geneva Motor Show. In the case of the Light Cocoon, 25% weight reduction for outer panels and lighter paper sheets are examples of the benefits brought by additive manufacturing to the structure of the car. In the aerospace sector, the Trent XWB-97 engine of Rolls-Royce was foreseen to carry out flight-testing in the course of 2015 and was said to be the largest 3D-printed aerospace component to fly[443] and led to a 30% lead time reduction.

[441] Both industries are indeed early adopters of Additive Manufacturing, in order for instance to speed up prototyping activities.
[442] See http://www.edag.de/en/edag/stories/cocoon.html
[443] Source : http://3dprintingindustry.com/2015/02/19/rolls-royce-to-fly-largest-3d-printed-part-ever-flown/

Figure 50: Summary forecasts for the 3DP market by industry

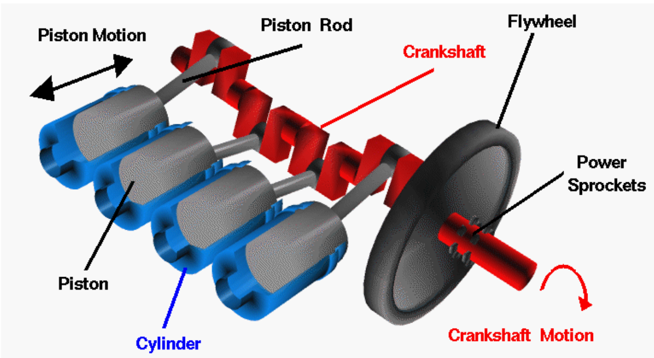


	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Other (millions)	277.1	325.2	442.4	571.4	702.2	842.9	999.8	1,185.8	1,397.8	1,650.9	1,898.7
Personal/Education (millions)	410.1	552.0	785.7	1,054.3	1,325.8	1,589.7	1,945.3	2,390.0	2,926.1	3,585.4	4,311.0
Auto (millions)	194.7	263.9	365.4	482.8	605.6	736.2	871.5	1,037.1	1,239.4	1,502.1	1,817.9
Dental (millions)	352.9	509.0	721.7	978.0	1,256.6	1,565.5	1,926.5	2,371.5	2,906.9	3,570.8	4,312.9
Medical (millions)	362.8	489.1	686.0	928.8	1,199.3	1,475.8	1,798.8	2,172.6	2,594.4	3,088.4	3,571.0
Aerospace (millions)	412.7	535.6	723.0	945.7	1,181.8	1,447.9	1,737.6	2,083.9	2,479.5	2,957.2	3,452.0

Source: SmartechMarkets Publishing in Forbes (2015)[444]

This case study is particularly concerned with **demanding components** such as gear boxes, powertrain parts, water pump wheels, and other structural parts but also (more specific to airplanes) engine parts such as turbine blades and fuel nozzles. These components are structural and necessary for the vehicle to function and move. They are usually concerned with mechanical issues such as one can observe in the case of the the simple reciprocating engine power train presented in Figure 51. The power train links the engine drive and the axle of a vehicle in order to transmit the power from the engine to the road. It encompasses many different parts such as the transmission, the engine, but also drive wheels, etc.).

Figure 51: Engine Power Train of the Wright 1903 Flyer



Source: NASA[445]

In the **automotive** but also in the motorcycle area (Ducati), manufacturers such as Lamborghini, Daimler, BMW, Peugeot, Mercedes, Porsche, Ferrari, Audi, SEAT, Renault, Volkswagen, Volvo, (as well as their equipment suppliers – EDAG, Faurecia, Continental and Bosch) investigate AM opportunities regarding structural components with professional AM service providers and printer manufacturers (like EOS, Beam-IT, Zera, Shapeways, SISMA and Trumpf) . Several manufacturers are involved in collaboration projects with universities such as Laser Zentrum Nord, Aachen University and Fraunhofer (DE), the University of Milan and, the University of Bologna (UNIBO), or the Universities of Salerno and Padua (IT). Beyond specific cases like Local Motors[446], frames are so far the main focus of most research done by industry (see for instance the Audi R8 for which AM was used to make space frame parts[447]). Recently, there is an increasing attention toward the demanding components that are part of the engine (which is part of the power train), for instance regarding AM in turbo-chargers (small but complex components of 2x4cm) as gains of elongation/elasticity are observed (from 10% to 20%) for some structural parts when using AM instead of traditional manufacturing techniques[448].

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[444] Available at http://www.forbes.com/sites/louiscolumbus/2015/03/31/2015-roundup-of-3d-printing-market-forecasts-and-estimates/

[445] See https://www.grc.nasa.gov/www/K-12/airplane/powert.html

[446] See for instance Local Motors, "*capable of making up to 3,000 3-D printed vehicles a year*" with AM technology as reported by http://www.nytimes.com/2015/01/16/business/a-3-d-printed-car-ready-for-the-road.html?_r=1

[447] Large alluminium parts, with a thickness of 2 to 4mm and a dimension of 1m40 per 50cm (height).

[448] More elasticity implies better security during a crash for instance.

In the **aircraft manufacturing** sector, AM was mobilized for structural parts in two three main ways:

- In order to print non-structural components, using for instance plastic AM such as in the case of the Airbus collaboration with Stratasys[449]. Those components are mainly used for the interior (cabin) of the aircraft and at the intersection between the structure of the airplane and its interior;
- To print jet engine components such as in the case of GE and Rolls-Royce[450];
- To print structural parts at the level of the structure (skeleton) of the aircraft and related demanding components but also secondary structural components such as Airbus' brackets (see Box 37).

According to Wohlers (2015), "*nearly all major aerospace OEMs, including Airbus, Bell Helicopter, GKN Aerospace, Honeywell, Lockheed Martin, MTU Aero Engines, Northrop Grumman, Pratt & Whitney, Raytheon, and Rolls-Royce, have built infrastructures within their corporations to evaluate and implement AM technologies*". Aerospace is crucial for countries such as France or the United Kingdom where it is expected to be the first area impacted by AM among 11 other sectors according to the Government's Industrial Strategy[451].

Figure 52: Series production manufacturing readiness level in the aerospace sector

Source: Adapted from Roland Berger, 2015

Aerospace is seen as one of the most mature areas where AM is close to full production for structural and demanding components (initially seen on production manufacturing readiness level 7-9)[452]. It is also strongly connected to other value chains when coming to Additive Manufacturing, such as Defense and Automotive applications and their underlying AM value chains. Beyond diverse possibilities offered by the technology (from organic shapes and graded/tailored materials to geodesic structures), AM is not only seen for manufacturing purposes but also for repairing (Allen, 2011). The repair market or – or Maintenance, Repair and Overhaul (MRO)[453], covers a key aftermarket industry. Rolls-Royce has for the last 5 years been using AM for repair[454]. An EU project funded under FP7, also known as "RepAIR", focuses on the matter of repairing parts using AM in the field of aerospace. The relevance of AM repairing for the aircraft industry is primarily linked to the price of an aircraft, which directly correlates with the willingness of airlines to keep each aircraft operational for a long period (Deppe et AL. estimate that 10 to 20% of airlines' aircraft operating costs are dedicated to MRO). The aircraft industry also presents a high level of demand for spare parts with several constraints like speed, efficiency, flexibility in the delivery of the replacement part with the penalty of carrying large stocks of spares. Early 2014, BAE Systems received approval from the European Aviation Safety Agency for AM spare parts for regional jetliners (more specifically window breather pipes) that costs 40% less compared to the originally ones produced with injection molding (Coykendall et Al., 2014). Many industry experts expect current applications to evolve towards the printing of large and complex systems (see for instance the expectations expressed in Figure 53).

[449] See http://www.stratasys.com/industries/aerospace/airbus

[450] See http://www.forbes.com/sites/timworstall/2013/12/02/both-ge-and-rolls-royce-are-to-use-3d-printing-to-make-jet-engines-by-violating-enginererings-prime-commandment/#60dde5f968e1

[451] On the basis of Analysis by Robin Wilson, 2014 – See the Positioning Paper entitled "The Case for Additive Manufacturing" published in 2015

[452] See Roland Berger, 2015

[453] Deppe et Al. (NoDate) note that "*The production and repair of spare parts for aircrafts is demanding and conventional technologies are limited in their ability to meet these requirements without using warehouses as a buffer while AM offers a new scope.*"

[454] Source: https://www.theengineer.co.uk/rolls-royce-breaks-additive-record-with-printed-trent-xwb-bearing/

Figure 53: AM applications in the Aerospace and Defense industry

	Current applications	Potential applications
Commercial aerospace and defense	• Concept modeling and prototyping • Printing low-volume complex aerospace parts • Printing replacements parts	• Embedding additively manufactured electronics directly on parts • Printing aircraft wings • Printing complex engine parts • Printing repair parts on the battlefield

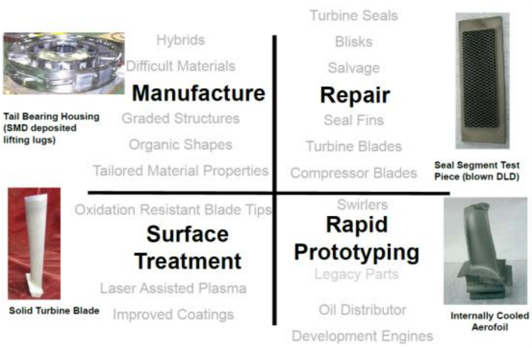
Source: Coykendall et Al., 2014[455]

(ii) Application area: metallic structural parts for aircraft

The initial case study area was formulated as "*Demanding components (e.g. gear box, powertrain parts, water pump wheel, structural parts) for cars and structural parts for airplanes, especially engines (e.g. turbine blades, fuel nozzles) (critical parts)*". The main interest in this area lied in its B-2-B nature and the possible links between this area and other value chains such as automotive and defense. The level of regulation and challenges with regard to certification also add to the interest of studying this application area. A first filter was adopted as structural and demanding components in the automotive sector have not yet reached a utilization level of AM that is mature enough (still limited to prototyping). Although the interest of the private entities is growing, the **AM of demanding and structural components in the automotive sector is currently focused on prototyping activities**. Two of the main reasons explaining this situation are 1) the cost and 2) the scale allowed by AM. These two factors are driving the industry (AM is mainly used for testing and prototyping in this industry).

The focus of **this case study will therefore be oriented towards aerospace**, and more specifically aeronautics. The aerospace sector is indeed the more advanced sector as AM has even reached production in few instances. As for many other sectors, the number of components effectively manufactured with AM is low. Additive technologies are however seen as promising for several types of application. Some of them are or could be subject either to manufacture, rapid prototyping, MRO or surface treatment such as suggested by Figure 54.

Figure 54: AM is being investigated for a multiplicity of uses



Source: Allen, 2011

In the aerospace industry, AM applications range from stator rings to fuel injectors (Wimpenny, 2013). Optimisation of processes and components are main drivers that foster the use of AM in that field. Players in the aircraft manufacturing sector also investigate issues such as light weighting and more efficient cooling. Some well-known applications in 2012 were:

- Turbine blades
- Physical 3D mock-ups
- Structured parts for unmanned aircrafts
- Customized interiors for business jets, private helicopters
- Swirlers / Fuel injectors by Morris Technologies
- Windshield defrosters by Adva Tech (Source: Somasekharappa, 2012).

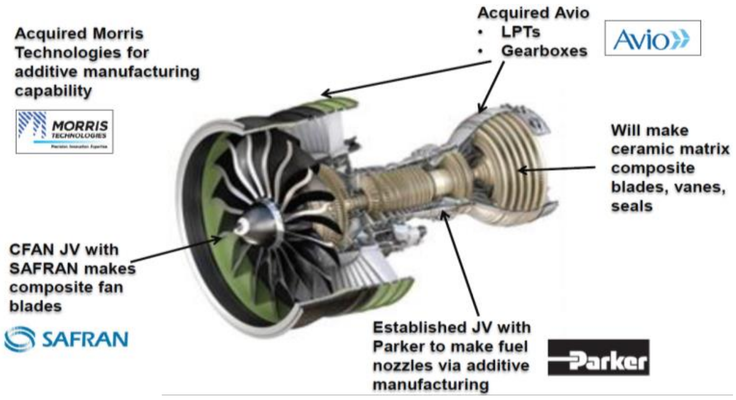
Many non-structural components are already being printed with AM for aircrafts[456], mainly with plastics. It is much less the case with demanding and especially structural components which are most likely to be printed with metal.

[455] See http://d27n205l7rookf.cloudfront.net/wp-content/uploads/2014/05/DUP_706_Figure-3_AM-applications-in-the-AD-industry.jpg

[456] For instance, according to the Engineer, "*Boeing, meanwhile, has several hundred types and tens of thousands of 3D-printed parts flying on its aircraft. These include 3D-printed parts on 10 different military and commercial aircraft production programmes, according to Leo Christodoulou, chief engineer for Boeing research and technology, materials and manufacturing technology. Boeing's suppliers have been using selective laser sintering to make small, polymer parts for*

Among the demanding components, the Aircraft **Engines segment**[457] attracted a lot of attention and is dominated by General Electric, Rolls-Royce and Pratt & Whitney[458]. All three companies are known to be involved in AM development. One of the most well-known success stories is General Electrics (GE) which is setting up "*mass additive manufacturing facility to produce 3D-printed fuel nozzles*"[459] used for the LEAP jet engines[460] (19 nozzles per engine in the LEAP case[461]). The LEAP engine developed in the context of a joint venture with Safran (Snecma) is 15% more fuel efficient thanks to AM and flew for the first time as part of the A320neo Airbus in May 2015. Between 2010 and 2015, the joint venture named CFM has received and committed to more than 2500 orders for the LEAP engine and is now on track for EU and US safety certification[462].Pre-orders have reached $135 billion[463]. GE is particularly active in AM (see Figure 55) but other players working on engines for aircrafts can be mentioned such as Rolls Royce (UK) or MTU (DE) . In November 2015, Rolls-Royce announced the first flight of its Trent XWB-97, the engine powering the Airbus A380 testbed aircraft in France: "*the first flight of the world's largest 3D-printed aero engine structure*" as the airfoils on the engine's front bearing housing were 3D-printed. The manufacturer explains that "*the Trent XWB, the world's most efficient civil aircraft engine, is also the fastest-selling wide-body engine with more than 1,500 engines sold to 41 customers*"[464]. Other parts of the A380 were developed using EBM[465].

Figure 55: GE vertical integration of the supply chain, including AM



Source: Michaels, 2014

In this case study, we do not focus on the engine, as the main engine components subject to AM are too mature as they have reached commercialization already. For example "*General Electric plans to mass-produce 25,000 LEAP engine nozzles with Additive Manufacturing (AM), and already have $22B in commitments*" according to Forbes[466]. The online AM media 3dprintingindustry.com noticed that "*Actual use of the LEAP engines on Airbus A320neo, Boeing 737 MAX and COMAC (China) C919 aircraft will begin in 2016, but, alongside news of Google's Project Ara smartphone, with 3D-printed components, GE's 3D-printed full nozzles represent the beginnings of 3D-printing used for mass production, rather than low-volume prototyping*"[467].

environment control system ducts (ECS) for military aircraft such as the F/A-18 Super Hornet and EA-18G Growler, as well as the company's commercial aircraft." (source: http://www.theengineer.co.uk/aerospace-takes-to-additive-manufacturing/)

457 Robin Wilson, lead technologist in high-value manufacturing (InnovateUK) has pointed at main applications in the field: "Aircraft manufacturers have invested billions in developing the use of metal powders through this technology to make turbine blades, jet engine combustion nozzles and structural parts "; an example quoted by Sia Mahdavi (Within – Autodesk) explains that "a fuel injection nozzle from GE, which was traditionally made in a laborious manner and comprised of 19 different components, can now be printed in one piece and is actually a lighter, better-quality component" (Source: http://raconteur.net/business/3d-printers-producing-factory-goods)

458 One should also note that "*Rolls-Royce is the current market leader and is estimated to have about 50% of the new orders in the most lucrative wide-bodied aircraft market, while GE holds about 40% of the new orders (…)Apart from the large OEMs and the corresponding joint ventures (with a regional emphasis on the U.S.), there are several suppliers in the global aviation engine market including MTU Aero Engines of Germany, Volvo Aero of Sweden, Avio S.p.A. of Italy and ITP Engines of the UK*" (Capgemini, NoDate).

459 Source: http://3dprintingindustry.com/2015/02/19/rolls-royce-to-fly-largest-3d-printed-part-ever-flown/

460 Source : http://www.gereports.com/post/116402870270/the-faa-cleared-the-first-3d-printed-part-to-fly/

461 Source : http://www.gereports.com/post/119370423770/jet-engines-with-3d-printed-parts-power-next-gen/

462 After 3660 certification test hours and 5460 test cycles

463 Source: http://3dprintingindustry.com/2015/04/21/3d-printed-jet-nozzle-cleared-fly-makes-aviation-history-135-bln-kickstarter/

464 Source: http://www.rolls-royce.com/news/press-releases/yr-2015/pr-06-11-2015-rolls-royce-trent-xwb-97-completes-first-test-flight.aspx

465 See http://www.sculpteo.com/blog/2011/09/20/eads-researchers-use-ebm-3d-printing-to-make-airbus-a380-parts/

466 See http://www.forbes.com/sites/louiscolumbus/2015/03/31/2015-roundup-of-3d-printing-market-forecasts-and-estimates/#634cab4f1dc6

467 Source: http://3dprintingindustry.com/2014/07/16/ge-announces-launch-mass-3d-printing-facility/

The choice is therefore made to select a close-to-market application area namely **structural parts made with metal AM**. A lot of potential is seen in the AM of such components, and especially "*large metallic structures*" (Ely, 2015). Wings and fuselage are central to this area, but also brackets and other structural (but in practice not critical) components (empennage, landing gears, stabilizers, etc.) are under the scope. As highlighted by Canaday (2015), "*Boeing 787s and Airbus 350s, for instance, are now built with at least 50 percent composites, with lesser amounts of aluminum, titanium, steel and other metals*". The 50/50 balance between metal and plastic-based materials still holds in the current airplanes. However, although polymers are seen as presenting future potential for this area, the AM part of the aircraft value chain is clearly dominated by metal and alloy (including iron, steels, and superalloys). This is of particular importance as Europe holds a key position in the metal AM market, with key players such as EOS, SLM Solutions or ConceptLaser in Germany. Also, the challenges encountered by the metal-based components regarding AM (wings and fuselage require for instance the printing of components that have large sizes) are critical to many other industries. Moreover, the focus on metal-based components also allows linking to the engine segment as the AM supply side of the value chain usually involves similar players in both application areas. Many such as Airbus see metal as the "*next step*" in AM for aircrafts: now using titanium, Airbus plans to start stainless steel and aluminum AM by 2017[468]. Also plastics can be used for demanding components, although such use is still emerging. In the US for instance SABIC, Stratasys, and Taylor-Deal Aviation created "*specialty fluid and air handling parts in hours rather than weeks while complying with Federal Aviation Administration (FAA FAR 25.853) and flame-smoke-toxicity regulations*" (Stratasys, 2013). The three partners called upon the use of Fused Deposition Modelling and ULTEM 9085 thermoplastic to address the challenge of obtaining parts with high "*strength-to-weight ratio, elevated thermal resistance, high strength and stiffness, and broad chemical resistance*". However, these cases remain very specific and do not yet appear as critical as applications like fuel nozzles.

Other demanding components made with metal AM are reaching a certain level of maturity: these are nacelle hinge brackets used to hold the engine nacelle cowling when it is opened. Box 37 depicts the well-known example of Airbus' brackets printed with EOS' technology.

Box 37: EOS and Airbus collaboration on the A320 nacelle hinge bracket

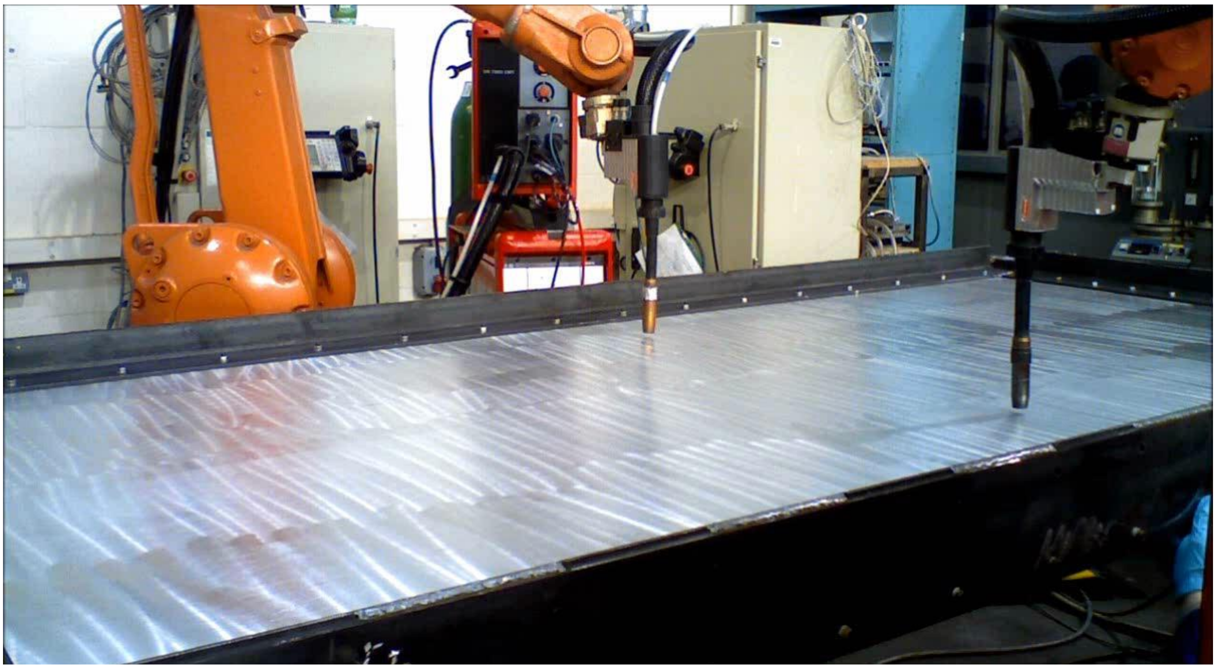
One of the main examples is a structural (non-critical component) component made of titanium: the so-called brackets. EOS and Airbus collaborated on an assessment, showing that with SLS, CO2 emissions over the lifecycle of the nacelle hinges would apparently be reduced by nearly 40% as the geometry and use of material would be optimized. Another result would be a weight gain of 10 kilos per plane according to the AM provider[469].

Source: EOS[470]

Although brackets such as the ones presented in Box 37 are among the most visible products, other parts remain relevant as well as they involve similar actors and technological features. One of the current developments progressively reaching adoption by the industry concerns the production of large parts and in particular wings. Although electron beam technologies are seen on the forefront of the production of large metallic parts, wire based processes using plaser, plasma or arc (Figure 56) deposition are now seen as being at the forefront of the production of large structural parts for airplanes. Figure 56 for instance shows a wire arc additive manufacturing (WAAM) process that is being developed produce large primary structural AM parts for wing and fuselage components.

[468] Source: http://3dprintingindustry.com/2016/01/04/airbus-is-ready-for-3d-printing-industrialization-in-2016-peter-sander-reveals/
[469] Source: http://www.eos.info/eos_airbusgroupinnovationteam_aerospace_sustainability_study
[470] See http://www.eos.info/eos_airbusgroupinnovationteam_aerospace_sustainability_study

Figure 56: Wire-based AM for the production of large airplane components



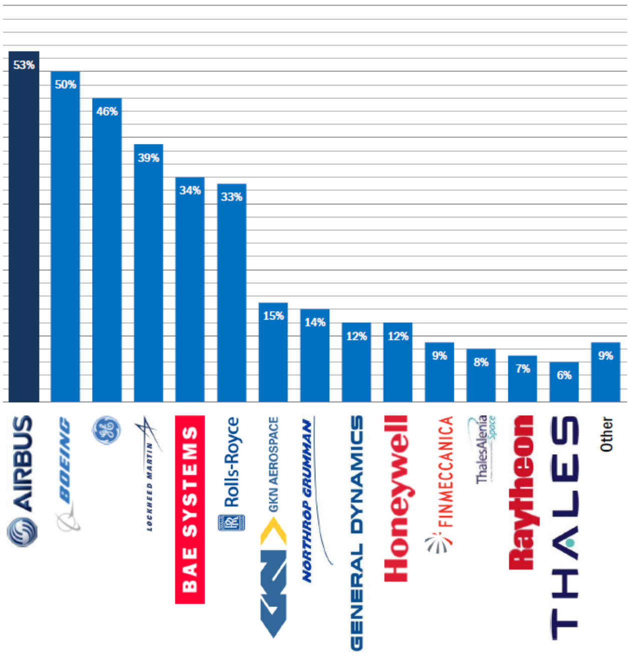
Source: Ding et Al., 2014

4.2.3.2 Identifying value chain components

(i) Identification of key players and usage of Additive Manufacturing

In the aerospace sector, the main players are large multinational corporations which have a lot of visibility and are known for taking the lead on key developments also in the AM community. R&D&I and/or AM managers in key companies were approached in order to gather relevant information. The analyses were also completed by interviews with space and automotive players in line with the position of this case study which aims to highlight the importance of the common interests of the three industries. The main AM players in the area are illustrated in Figure 57.

Figure 57: Aerospace and Defence market leaders in additive manufacturing



Source: Defense IQ, 2016[471]

[471] Survey implemented by Defense IQ and targeting 126 industry professionals.

Most of the Value Chain models are in line with the developments of engine components (see Figure 59). Examples of companies and collaborations on AM in the sector include the following:

- GE[472] and Rolls-Royce are two prominent examples of firms that gained a lot of publicity with their AM activities. The global players at stake are indeed limited and their success stories are highly visible. They are active on all continents: GE and Honeywell (US-based) compete for instance in Italy and GE is to open facilities in Romania and is cooperating with Safran (FR).
- The Spanish player Harcotera is developing AM for Boeing[473] - more specifically regarding the Boeing 787 jet engine –, while Airbus collaborates with Stratasys on the production of a broad range of components.
- AvioAero works on the engine parts: together with Arcam AB, this branch of GE worked on the AM of turbine blades for the GE9X Engine[474]. The collaboration involved the Japanese IHI Corporation, Snecma (Safran, FR), Techspace Aerospace and MTU Aero Engines (DE)[475].
- Altair (DE) has been promoting its cooperation with EADS (now Airbus Group) on the design and AM of brackets in many instances.
- Arcam also worked with Pratt & Whitney on the entry-into-service jet engine parts of the PW1500G engines at the production level, with particular emphasis on compressor stators and synch ring brackets.
- From the US, Boeing is known to use AM extensively and aims towards more metallic AM and even patented in that direction[476].

Box 38: Rolls Royce' Trent XWB-97 engine

In Europe, Rolls Royce made in different instances the case of AM for aero engines and even made use of EU funding in that regard (such as through the FP Project FANTASIA). The aforementioned Trent XWB-97 engine is seen as the British competitor of General Electrics' AM lead products: 48 titanium aerofoils manufactured with EBM resulted from the cooperation between the industrial leader, the Sheffield University and UK's Manufacturing Technology Centre.

Source: Rolls-Royce[477]

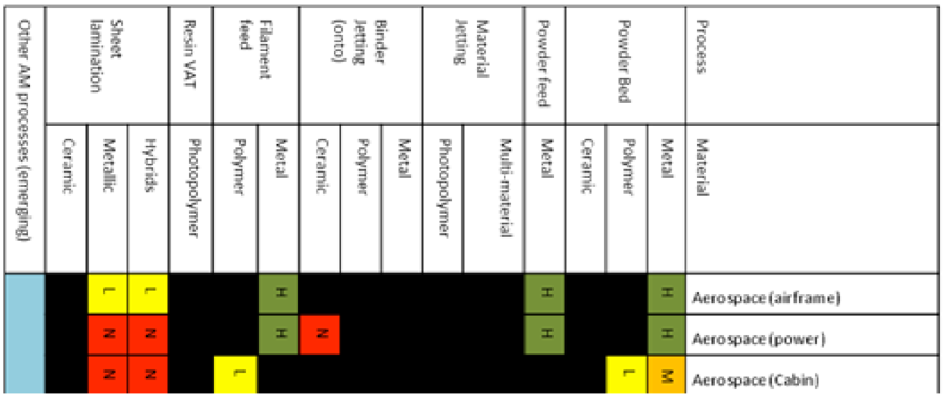
Particular cases such as the collaboration between Boeing and Lotus F1 on the AM of carbon-reinforced parts[478] could be identified, as well as a spare parts certification case: "*BAE Systems received approval from the European Aviation Safety Agency (EASA) for its additively manufactured window breather pipes used in regional jetliners. 60% cheaper than pipes made through injection molding, AM pipes are printed then shipped to customers when required*"[479]. In the case of EBM cases, Arcam AB (SE) is seen as the main AM supplier, providing EBM machines to the healthcare and aerospace sector with particular emphasis on titanium (and to some extent aluminum) printing. Service providers were also identified as they work in cooperation with both OEMs – Tiers 1, 2 and 3 suppliers – and integrators (Hiemenz, 2013). Countries where aeronautic players are historical industrial leaders are mainly concerned by the effective adoption and deployment of AM: this is the case of France, Germany and the UK. "*Within the aerospace sector, companies including Boeing, Northup Grumman, GE and Honeywell all have highly developed large internal AM research groups, as have companies such as EADS and Avio*" (Source: Special Interest Group Additive Manufacturing, 2012).

In order to identify key players and approach the AM value chain under the scope, one has to understand the main technologies driving this value chain. In the particular case of demanding components, powder-based technologies dominate the area: Selective Laser Melting (or "*SLM*"), Electron Beam Melting, also pointed at as "*EBM*" as well as Selective Laser Sintering ("*SLS*") are visibly used – although the latter appears to be less common to the field[480]. Another key technology, this time wire-based, is being developed in the context of a science-industry partnership that is most likely to come up as a competitor to EBM regarding the production of large structural components for airplanes. A first screening of the sector in the UK led to the findings observed in Figure 58 which still hold valid today, although the AM technology landscape seems to be moving. One of the reading keys to be adopted for this particular case is the technological one: Laser-based technologies are used for small and complex components while EBM, Wire and fused deposition are more adapted to the AM of larger components (1m²<).

[472] General Electric is perceived as one of the world-wide leaders in the market. The American company is indeed present in a number of AM application areas, ranging from Energy (where turbine blades are 3D-printed) to the software area.
[473] See http://3dprintingindustry.com/2015/09/01/spanish-maker-3d-prints-working-model-of-boeing-787-jet-engine/
[474] After validation, these blades are planned to be produced with EBM from 2016 onward (source: Arcam AB, NoDate).
[475] See http://3dprintingindustry.com/2014/08/11/3d-printing-ge-jet-engine/
[476] See http://www.tctmagazine.com/3D-printing-news/boeing-files-patent-for-3d-printing-aircraft-parts/
[477] See http://www.rolls-royce.com/media/press-releases/yr-2015/pr-06-11-2015-rolls-royce-trent-xwb-97-completes-first-test-flight.aspx
[478] See http://3dprintingindustry.com/2014/07/16/boeing-lotus-f1-team-3d-print-carbon-reinforced-parts/
[479] Source: http://3dprintingindustry.com/2015/06/02/7-key-improvements-3d-printing-brings-to-the-aerospace-industry/
[480] One non-EU example is depicted on http://3dprint.com/82169/3d-printed-aircraft-parts/ where the production cycle of an airplane frame component would have been reduced by 80%

Both are however considered in this case study as they involve similar players and are somehow aimed towards competition due to the current technological advancements that will be referred to along the presented analysis.

Figure 58: AM techniques mobilized in the aerospace sector



Process	Other AM processes (emerging)	Sheet lamination			Resin VAT	Filament feed		Binder Jetting (onto)			Material Jetting		Powder feed	Powder Bed		
Material		Ceramic	Metallic	Hybrids	Photopolymer	Polymer	Metal	Ceramic	Polymer	Metal	Photopolymer	Multi-material	Metal	Ceramic	Polymer	Metal
Aerospace (airframe)			L	L			H						H			H
Aerospace (power)			N	N			H	N					H			H
Aerospace (Cabin)			N	N		L									L	M

Source: Special Interest Group Additive Manufacturing, 2012

The value chain of AM applied to the aerospace sector is usually understood in terms of the main technical steps associated to the printing of a .stl file. These steps are depicted in Figure 59 and cover the design of a 3D model (Step 1) that is converted into .stl format. Step3 corresponds to the virtual slicing of the file before it is sent to an AM system for printing in Step 4. Step 5 corresponds to the final post-processing that should lead to the end product.

Figure 59: AM flow in the aerospace sector

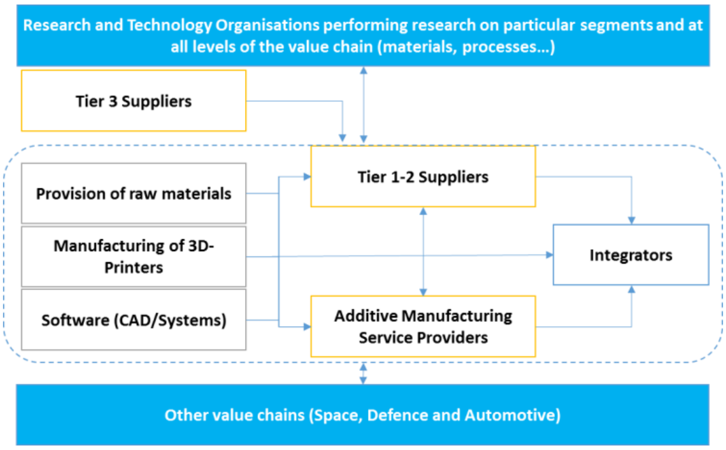
Source: Coykendall et Al., 2014

Although it is useful to understand the design and printing of an aerospace part, this figure does not account for the economic realities of the sector. For instance, the collaborations mentioned in this section suggest that companies intervene at different stages of the value chain.

(ii) Composition of the value chain

Figure 60 depicts the main segments of the value chain as approached during this case study. In this figure, Tier 3 suppliers are seen as piece part manufacturers while Tier 2 players focus on component manufacturing. Tier 1 suppliers (integrators of components into sub-systems) provide integrators who are on the front stage.

Figure 60: Main segments of the aircraft structural parts additive manufacturing value chain



One of the particularities of the aeronautic AM value chain is that integrators and OEMs on a Tier 1 supply level seem to be moving along the value chain. This is the case for example for some OEMs dealing with raw materials such as GKN through Hoeganaes[481] or Airbus with its Scarmalloy[482] for structural applications. Another example is GE that absorbed two AM companies in 2013 – Morris Technologies and Rapid Quality Manufacturing (RQM)[483]).

Provision of raw material

This case focuses on structural parts made with metal AM. The metallic powders are usually provided by companies like Eurasteel EU or Metallo-Chimique N.V. (BE), TLS (DE), LPW (UK), Constellium (NL), Google[484] (US), ATI (US), AMPS (Australia), Sandvik (SE), H.C. Starck[485] (DE), Carpenter (US), but also world-wide providers from Canada (Equi-Sphere for instance) and smaller EU companies from Spain. Regarding aluminum in particular, Valimet (US), TLS (DE), NMD (DE), and ECKA Granuls (DE) were mentioned during the interviews; and although iron is not much emphasized, Aubert et Duval (FR) was referred to by one of the interviewees. High volume producers would mainly be American (Kymek in the US and APNC in Canada). Titanium aluminide (with a higher level of resistance than classical titanium – around 800 degrees Celsius instead of 500) would be the primary material used by AvioAero in Italy for the engine blades, while usual titanium would be more adapted to structural components as it does not need high temperature resistance.

One of the fundamental constraints for the use of powders relates to the guarantees of the printer manufacturers which try to lock-in their role on the value chain as they require customers to use their powders should the customers wish the guarantees over their printer(s) to remain valid. Here, customers referred to important margins taken by the AM printer manufacturers compared to the case in which powders would be bought independently from providers.

More specific to the aerospace sector however is the strong uptake of powder development activities by GKN. Beyond its activities of aerostructure, engine and propulsion systems' manufacturer, GKN is involved in powder development through its Powder Metallurgy division[486]. Particular efforts are for instance being dedicated by this division to the 3.1M£ TiPOW collaborative project supported by the British government and aiming to the development of "*titanium powder specifically formulated and blended to meet the needs of additive manufacturing (AM) of aerospace components*"[487]. In 2013, the sales of the powder metallurgy division (12% of overall sales) reached £932M (while £2.243M were generated by the aerospace division). Also Airbus is considering similar activities.

[481] See http://www.gkn.com/hoeganaes/products/Pages/Additive-Manufacturing.aspx
[482] See http://www.technology-licensing.com/etl/int/en/What-we-offer/Technologies-for-licensing/Metallics-and-related-manufacturing-technologies/Scalmalloy.html
[483] Source: Coykendall et Al., 2014
[484] As to illustrate the involvement of Google in AM, one can refer to its patenting activities, such as presented on http://www.google.com/patents/WO2013167194A1?cl=en
[485] Also Global Robots, PKM in Spain, MAZAK and IRDS were referred to by an interviewee but not confirmed as being effectively involved in the value chain under the scope.
[486] Source: http://3dprint.com/59084/tipow-research-collaboration/
[487] Source: http://www.gkn.com/media/News/Pages/GKN-Aerospace-commences-collaborative-research-to-create-additive-material-for-aerospace.aspx

Manufacturing of 3D-Printers

The key determinant of this segment of the value chain is the material used, metals in our case, where the EU industry demonstrates key strengths compared to the world-wide competition[488] and one of the few areas where it does not suffer from American competition (as EOS, SLM Solutions and ConceptLaser from Germany lead this market, followed by their British counterpart Renishaw[489] and Arcam AB from Sweden). Titanium would have mainly been emphasized by companies like Arcam and Evonik (DE) while alluminum would be a matter of SLM Solutions, EOS and ConceptLaser. From a different perspective, companies like Voxeljet and ExOne find themselves indirectly involved in this value chain as they produce AM printers used for tooling and the printing of mold inserts that will be used either for rapid prototyping or for the production of components[490].

Software (CAD/Systems)

A difference should be made between two types of software. First, operating (system interface level) software such as 3-matic and Magics software from Materialise [BE] are necessary to operate printers such as EOS' (DE). In the same way, SolidView from Stratasys [US] (and others, such as Netfabb [DE]) are essential.

Second, design software are used to design the files to be printed and referred to as CAD (computer assisted design) software. Main CAD software in the aerospace sector are Simpleware (UK), Materialise' softwares, WithinLabs (based in the UK but belonging to Autodesk, US), NSPI (US), Hyperworks and Optistructs (DE). The usual CAD software are still dominating the market, with Altair's OptiStruct and PolyWorks but also Dassault's SolidWorks and Catia softwares (FR) or Autodesk's AutoCAD. The CAD part is particularly dependent on the knowledge of integrators and Tier 1 and 2 suppliers as the design professionals should make use of their component expertise. The designer usually needs to have a detailed knowledge of the component: thus the design phase is most likely to take place at the level of integrators. These integrators would then send the resulting .stl file to an AM service provider or process to the printing in-house. Although the CAD environment remains dominated by "usual suspects", new developments seem to be on-going on the side of the system software where many AM users with design and software capabilities tend to enter the competitive arena.

Important moves are visible on the software segment as many companies (machine manufacturers but also service providers) try to develop their own software solutions – whether system-wise or regarding particular aspects of the design or the interface (such as regarding the positioning of components in the chamber).

Tiers 1 and 2 suppliers (OEMs)

Tier 1 and 2 suppliers mainly provide components and sub-systems to be integrated into final systems. These companies, often large international players, are interested in both the provision of inputs and the services they will be able to provide to integrators.

The range of equipment and components produced by OEMs is broad: AvioAero (IT) for instance, the GE branch in Italy, works on mechanical transmissions, turbomachinery, combustors, frames and cases, Additive Manufacturing, MRO & CRO[491], and sand casting. Today, the GE branch has a factory dedicated to AM where 20 EBM printers are functioning together with an unknown number of laser machines, all turning towards production activities. According to an interviewee, this example illustrates the necessity of the large investment required from companies willing to upgrade their AM capabilities to a production level (note that he nozzle success story of GE was the result of $1B investment in R&D[492]). The main players are anchored in the US and EU.

Other companies active in Tiers 1 and 2 segments are SAFRAN (which is also the French umbrella of SNECMA) and Zodiac Aéro. Also companies such as Finmecannica (which collaborates with civil aircraft manufacturers on structural parts) or the Airbus branch Aviospace do not use yet AM but are exploring the opportunity to integrate the technology and take a step further. Collaborations are important to the sector: GE is involved in a 50/50 joint venture with SNECMA to produce the LEAP engine and Airbus invested in Local Motors after entering in a partnership with Stratasys for the production of 1000 non-structural flight part of the A350 XWB aircraft[493] with FDM[494].

488 The main metal AM players are in order of importance EOS, Concept Laser, Arcam, Phenix Systems (now 3DS), MTT Technologies, Trumpf, ReaLizer, SLM Solutions and Renishaw (Source: SIRRIS, 2014)

489 See http://www.renishaw.com/en/renishaw-supports-uk-government-funded-additive-manufacturing-aerospace-initiative--27335

490 An interviewee explained in that respect that "*wire based equipment is more versatile and available and considerably less captical cost (per working volume) than that of bespoke powder based manufacturing equipment. The use of conventional welding equipment (such as Fronius CMT) and classic multi-axial robotic arms (ABB) all driven by bespoke control software ihas the potential to be the least expensive and most versatile solution*"

491 Maintenance Repair and Overhaul & Component Repair and Overhaul

492 See http://3dprintingindustry.com/2014/08/11/3d-printing-ge-jet-engine/

493 See http://blog.stratasys.com/2015/05/06/airbus-3d-printing/

494 Using "*ULTEM 9085 thermoplastic, which is FST (flame, smoke, and toxicity) compliant for aircraft interior applications*" (Source: https://www.onlineamd.com/article/stratasys-additive-manufacturing-composites-europe-080815)

AM Service Providers

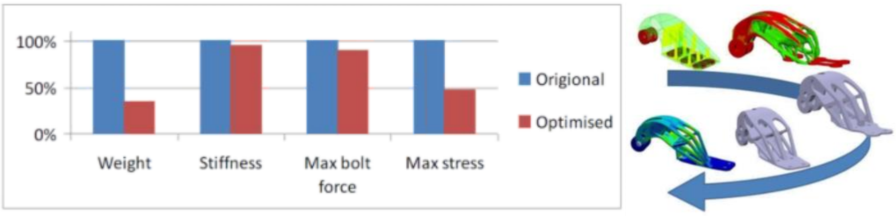
AM service providers have a different role in the value chain as they provide key inputs to large manufacturers and are often pushed by their clients towards the adoption of AM and development of capabilities thereof. The close collaboration between printer manufacturers and aircraft manufacturers also lead the former to produce parts for their clients while in a more decentralized value chain setting, the service providers would have done so.

Service providers are mainly located in France: Airpro, Polyshape, 3A (which won an AFPR award for the EBM production of titanium alloy parts for Dassault), FUSIA, Spartacus 3D (originating from the Faramir foundry group), and engineering companies turning to AM developments like Sokaris, PRISMAD, Polyshape (which teamed up with LISI), and Mecachrome. These companies collaborate with OEMs and integrators on brackets and structural parts.

Box 39: Collaboration between EADS and Altair

Also service providers like Altair closely collaborate with airplane manufacturers: while it was still EADS, Airbus engaged in an optimization process with the engineering company to get brackets to weight from 326g when produced with AM instead of 918g (weight loss of 64%). The expertise brought here was rather at the design level and in terms of competences regarding the HyperWorks software used for the optimization of the structural component (see Figure 61). In terms of AM production, Airbus would rely on Premium Aerotec (PAG) in the North of Germany where a first ALM Factory would have opened with 4 printers[495].

Figure 61: Performance comparison of original and new design of the Altair-EADS Bracket



Source: courtesy of Altair

Integrators

The main integrator referred to so far is the leading European player in the field, Airbus. However, it is not the only one, also Bombardier is active in Europe as well as Sikorsky in Poland. Airbus pushes AM developments: the SLM-optimized cabin brackets of the A350 flew for the first time in 2014[496] (see Figure 62) and many cooperation agreements have been spotted between the industrial leader and EU organizations (whether printer manufacturers, service providers, or RTOs,). Airbus like other integrators faces pressures for more efficient systems, optimized end products, and therefore lighter parts. Following that line of thinking, the company developed many AM activities and plans to "*3D-print around 30 tons of parts monthly by 2018*"; the group also upgrades its HR and involved around 60 employees in about 120 AM projects in Germany (source: Wohlers, 2015).

Figure 62: AM bionic titanium bracket for the A350 XWB

Source (from left to right): http://www.a350xwb.com/photo-gallery/ and http://www.airbus.com/presscentre/pressreleases/press-release-detail/detail/printing-the-future-airbus-expands-its-applications-of-the-revolutionary-additive-layer-manufacturi/

[495] Source: http://3dprintingindustry.com/2016/01/04/airbus-is-ready-for-3d-printing-industrialization-in-2016-peter-sander-reveals/

[496] See also http://additivemanufacturing.com/2016/01/27/airbus-group-pioneering-bionic-3d-printing-learning-from-nature/

Safran is another player which follows similar objectives than Airbus: it aims to upscale its AM activities by 2020. In addition, also Lockheed Martin and Bombardier[497] (UK/Northern Ireland) as well as Rolls Royce are developing AM capabilities[498]. In France, Dassault is a central player that is developing AM in a rather discrete way.

Research and Technology Organisations
There exist a number of collaborations between private and research actors focusing on the processes regarding 1) Systems and 2) Materials. Several universities in the UK (Sheffield, Cranfield, Manchester, etc.) collaborate with players from the aerospace industry. Other examples include Politecnico di Milano which is highly involved in the development of CAD and 3D scanning systems[499], the collaboration between Airbus and the Laser Zentrum Nord GmbH (LZN) in Germany and Cranfield University[500] in the UK.

Particular entities (TWI (UK), TNO (NL), Fraunhofer or the Direct Manufacturing Research Center (DE)) are exploring new pathways, while technical centers such as CTIF and CETIM[501] (FR) tend to focus on assisting industrial players in order to facilitate the adoption of AM solutions by both manufacturers and OEMs. Collaborations is fundamental to this value chain and is the motor of key advances. The UNIBO (IT) collaborated for instance with AvioAero (GE branch in Italy) on the AM of metallic alloy blades depicted in the introduction and is now paying more attention to the possibilities to demonstrate AM of structural metallic components. Relevant French research Centers are Mines de Paris, INSA, UTC, or UTBM.

Connections with other value chains
The nature of the components and materials (frames and engine parts, titanium, aluminum, etc.) make the developments taking place in the aerospace industry similar to developments in other industries. This is particularly the case of the automotive, space and defense sectors which also investigate AM potential for optimisation for example. The OEMs involved in the aeronautic value chain are also very often involved in these other sectors as they supply car or military vehicle manufacturers with parts or sub-systems. The aeronautic sector is also strongly related to the military aircraft, helicopter, and weaponized systems. Therefore companies such as BAE Systems, the US-based Lockheed Martin (from its location in the UK), Liebherr, Finmeccanica, MBDA (including Roxell) are to be mentioned.

One of the main examples is the one of Space applications as depicted in Box 40: although airplane and space AM value chains are different and know different drivers, they share many commonalities such as regulatory constraints and similar AM components.

[497] Airbus and Bombardier are mainly working on the AM of primary structure applications, driven by titanium components used to join components (of less than 3m) of the structure together (for instance with direct deposition techniques) and the growing use of composite materials.

[498] See for instance their involvement in the AMAZE project supported by the EC (www.amaze-project.eu/ *and* http://www.reuters.com/article/norsk-titanium-as-idUSnBw035840a+100+BSW20151203)

[499] See Fino and Ugues, NoDate

[500] See http://www.altairuniversity.com/13858-airbus-cranfield-university-double-speed-of-titanium-part-production/

[501] In France, the CETIM is trying to build for itself a central position in the regional ecosystems: for instance, it leads a project entitled SUPCHAD and aimed at "Mutualisation de moyens technologiques pour la constitution d'une supply chain aéronautique en fabrication additive" (Budget: 1,2M€). See http://www.cetim.fr/Actualites/En-France/A-la-une/Fabrication-additive-partagee-au-Centre

Box 40: Eye on - Aerospace AM Brackets

Clear similarities are to be highlighted between civil aircraft manufacturing and space applications, which are also subject to difficult environments (correlating with regulatory requirements) and high levels of investment. Although they strongly differ in many regards (and mainly regarding the number of parts produced), they involve common players and share technical concerns which translate into development opportunities. Altair is for instance one among many other engineering companies involved in the AM-design of aerospace components. One of their key successes is related to the design of brackets for satellites, in cooperation with Ruag and EOS (see) for which the HyperWorks software was mobilised. A similar interest for brackets was identified in the Airbus Group which developed (in cooperation with LZN, the ILAS-Institute of Laser and System Technologies and ConceptLaser) DMLS-optimized nacelle hinge titanium brackets for the A320[502]. A 64% weight reduction can potentially bring important savings, as "*removing one pound of weight from each aircraft of a 600+ fleet of commercial aircraft could save about 11,000 gallons of fuel annually, cutting down on fuel bills—which, as of 2013, typically absorbed 35 percent of an airline's annual revenues*" (Coykendall et Al., 2014). Altair and Airbus collaboration on the bracket presented on the top right-hand side of this box relied on the use of the HyperWorks software. On the bottom right-hand side, another bracket example is given that was driven by optimization concerns (picture source: Dumani, 2014[503]). Oak Ridge National Laboratory (ORNL) and Lockheed Martin also collaborated on the AM of BALD brackets produced with EBM[504].

In aerospace, satellites (injection system and many other parts[505] - using platinum-based alloys and aiming towards aluminum) and launchers (brackets and propulsion system – using titanium) are the main subjects of AM. These applications involve players such as

- ThalesAleniaSpace, Airbus Defense & Space and its branch Aviospace, Honeywell Aerospace, GE, OHB, Mecachrome, SNECMA, PrimeIndustria;
- Materialise, Layerwise[506], Polyshape (working with ThalesAlenia), Initial (now Gorgé), Beam-IT, Prisma, Fusia as well as several French SMEs surrounding the Italian Aerospace cluster of Apulia;
- Arkema, Stratasys, and 3DS (the three companies seem to control an important part of the material provision);
- Technical centres such as SIRRIS (BE), CETIM (FR) and LZN (DE);
- Major public institutions such as the ONERA, CNES, NLR (NL), DLR (DE) and the ESA;
- Intermediary organisations (AFNOR, GIFAS, ASTECH Competitiveness Cluster in France)
- Universities and other RTOs such as TNO (NL), KUL (BE), IRT St Exupéry (FR), Scatech (ES), TWI (UK), Cotech (AU), FhG (ILT in particular) (DE); the Tallin Institute of Technology).

[502] Among other sources was InnovateUK funding

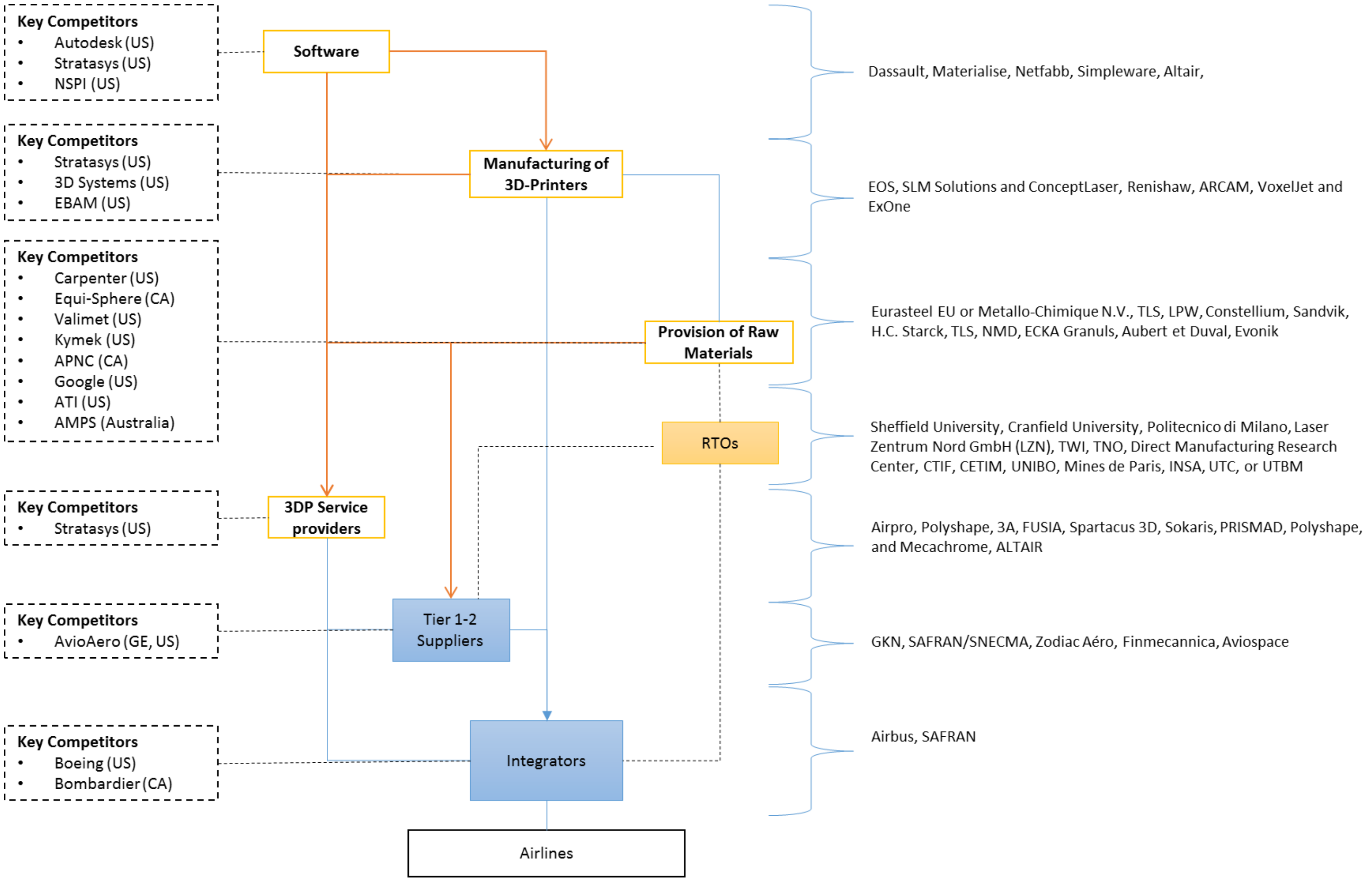
[503] In reference to http://www.airbusgroup.com/int/en/story-overview/factory-of-the-future.html

[504] Source : Newell, 2013 – available at web.ornl.gov/sci/.../docs/AM&P_March%202013_cvr_w-articles.pdf *web.ornl.gov/sci/.../docs/AM&P_March%202013_cvr_w-articles.pdf*

[505] Such as payload, RS components, antennas, brackets for antennas, release mechanisms, deployment mechanisms, brackets for the structure, heat pipes and heat loops, cryostat, etc.

[506] Layerwise (BE, now 3DS) is for instance involved in the production of structural space components for satellites.

Figure 63: Illustration of the airplanes structural parts additive manufacturing value chain



Source: IDEA Consult, 2016

Note: the names of the organisations mentioned are only included for illustration purposes and no colour code was applied – colours codes were only added to make the figure more readable.

(iii) Functioning of the value chain and critical factors

The value chain of AM of structural components for airplanes is highly concentrated and mainly defined by its technological orientations (so far, metal-based AM techniques determine most of the value chain). Different business models are observed in the value chain of AM of structural components for airplanes. The high level of concentration and growing prominence of tier 1 suppliers make the number of players with enough critical mass to absorb AM technologies identifiable. It reveals a strong – though still prudent – approach to the further developing of AM. European players and American players clearly occupy the stage and compete almost on a one-to-one basis (GE vs Rolls-Royce, Airbus vs Boeing, etc.). The particularity of this value chain remains that it links quite strongly (and could link even more strongly) to other sectors (space, defense, automotive) dealing with similar AM needs and challenges. Also, AM seems to be seen as part of an evolution of the value chain as Tier suppliers seem to move along the value chain.

Referring to AM in the aerospace sector as a whole, an interviewee noticed that three main business models were to be observed in the field. This view was confirmed by other interviewees:

- The GE model (through AvioAero) is an in-house approach where the OEM is willing to do everything itself and limits the scope of its cooperation activities in order to retain skills, knowledge and keep control over the value chain.
- The Airbus model on the contrary is based on partnerships and follows a distributed approach, pushing down the value chain towards the upgrade of its suppliers' capabilities (one of the interviewees noticed that GKN is currently most likely to have more AM systems than Airbus itself). Airbus therefore aims towards more focus on the design and specifications, while production is expected to be outsourced to other players.
- Tier 1 and 2 players: Tier 1 and Tier 2 are exploring, developing and upscaling AM in their organisations on the basis of individual programmes. These companies starting from conventional technologies (milling, casting, etc.), anticipate on AM parts to be developed in aeronautics but have no influence over these.

In most cases[507] the main driver fostering AM advances is the search for savings: here, lead time reduction and product optimization that will lead to savings in the aeronautic sector due to regulatory and economic pressures. Other longer-term benefits could include the diminution of tooling, stocks, etc. as AM could allow on-site printing of spare parts. Design freedom, optimization and components integration and on-demand production are appealing to manufacturers: the aircraft manufacturing sector is indeed one of the sectors where AM could lead to localized production. One particularity of this AM value chain is that it is concerned with the production of smaller series than in other sectors (tens of thousands instead of the million parts sought in the automotive industry). Thus AM is less concerned with the limitations encountered in sectors that are driven by scope and scale such as automotive. Also, a key parameter that frames the entire development of AM for structural parts in this area is the importance of safety regulations. As a result, airplane developments usually take several decades: the development time, including for AM development and further deployment, is therefore rather long. However, the possible spill-overs to other industries are not to be neglected. One can note that the aeronautic is strongly interlinked with the engine AM value chain and that many connections are to be found (whether through the components or actors involved) between aeronautics, space, automotive and defense applications.

In the Aerospace industry[508] competition is rising from China[509] but also from the US regarding the rise of polymers and composite (including ceramic-based) AM components. As to illustrate this fact, one should note that a competition between polymer and metal AM is associated to the Boeing-Airbus competition. Also, China seems to be catching up with the certification of the Comac C919 aircraft AM parts[510].

With regard to the competitiveness of EU players in this area, the topic of materials is important to consider. Several interviewees pointed at the role of printer manufacturers and their business strategies to draw margin on the supply and mandatory use of specific powders, creating bottlenecks for many AM end-users, while many powder providers are currently active in Europe. The strategy of printer manufacturers would rely on the conditionality associated to the guarantee they provide: by making the guarantee conditional to the use of their own powders, these players manage to keep other powder providers out of their community of clients.

The current investments and publicized commitments of aeronautic players in the uptake and deployment of AM techniques towards production are promising. Tooling, life-cycle management, and in particular prototyping and mainstream production are seen as the upcoming fields of use of AM in A&D (Defense IQ, 2016) for a faster production of larger parts, multi-material printing and printing of embedded parts (Automotive IQ, 2015). The rising price of oil is also expected to push aircraft manufacturers towards more efficient (and therefore lighter) systems to produce less environmental externalities. Some interviewees see AM of mechanically loaded parts as a first step. Material-related evolutions towards an increasing use of composite materials in structural parts in airplanes (as supported by Canaday, 2015) might also be foreseen; but these developments, should they effectively take place, might take decades.

[507] This does not apply (or only to a limited extent) to wire-based technologies.
[508] See https://www.onlineamd.com/article/stratasys-additive-manufacturing-composites-europe-080815
[509] See http://3dprint.com/82169/3d-printed-aircraft-parts/
[510] See http://aviationweek.com/commercial-aviation/comac-c919-have-3-d-printed-titanium-spars and http://usa.chinadaily.com.cn/epaper/2013-08/13/content_16890538.htm

The development of adapted monitoring systems is predicted to be followed by better 'control'. While monitoring allows for seeing mistakes, control would allow anticipating on mistakes: with monitoring tools one can indeed follow the production process and identify mistakes, while control would allow anticipating and mastering the possible mistakes. New developments are also coming up. Airbus is exploring the possibility to pursue further system integration in the future, with the possibility to print major plane sections together. In that sense and back to the engine segment of the aircraft value chain, GE Aviation finalised in the course of 2015 a miniature engine of which all parts were all 3D-printed (in metal) and then assembled (see Figure 64) before the engine was taken to 33,000 RPM.

Figure 64: GE miniature engine entirely 3D-Printed

Source: GE REPORTS, see http://www.gereports.com/post/118394013625/these-engineers-3d-printed-a-mini-jet-engine-then/

4.2.3.3 Missing capabilities

(i) Regional Dimension and missing capabilities

There is a clear concentration of the aeronautic AM segments in Western Europe and in particular in France, Germany, Italy, and the United Kingdom. It mainly concerns powder-based technologies as most of the other techniques to compete in this area are not yet available on the market – although several wire-based systems are currently going through a demonstration phase. The main players on the segment of printer manufacturers are located in Germany while the key aeronautic players in demand of AM technologies and services are either located in France, the UK or Germany.

- From a materials point of view, companies are mainly active in Benelux, Germany and the UK. Key players in that field include GKN (North Rhine-Westphalia), Erasteel (North Rhine-Westphalia), Eurasteel (Flanders), ECKA (Bavaria), Constellium (North Holland), Sandvick (Flanders), Aubert et Duval (Auvergne) LPW (Cheshire). They compete with ATI and Nanosteel (US), AMPS (Western Australia) but also Canadian companies such as Canada Powder (Ontario). However, interviewees pointed at a serious lack of capabilities in terms of powder supply, and in particular in the fields of aluminum and titanium (fields in which China dominates the world-wide market, followed by India and North America).
- Service providers could mainly be identified in France and to some extent in Belgium where Materialise (Flanders) has an important role. Companies such as Sokaris (Ile-de-France), Spartacus 3D (Burgundy), 3A (Ile-de-France) and Altair (Baden-Württemberg) were identified. Also FUSIA is part of this group and is located in the main French aeronautic cluster (Midi-Pyrénées).
- Printer manufacturers are concentrated in Germany and to some extent the UK and Sweden: Arcam (Västergötland), Renishaw (Staffordshire) and the German companies SLM-Solutions (Schleswig-Holstein), EOS (Bavaria), Voxeljet (Bavaria), ExOne (Bavaria) and ConceptLaser (Bavaria) are the main actors in the field.
- The RTOs are mainly based in Western Europe but it seems that their geographical repartition touches upon more countries: Sintef (Sør-Trøndelag), Aachen University (North Rhine-Westphalia), LZN (Hamburg - Low Saxony), Fraunhofer (Bavaria, Hesse), CTIF (Rhône-Alpes), TNO (South Holland), Ecole des Mines (Ile-de-France), CETIM (Rhône-Alpes), University of Padua (Veneto), University of Bologna (Emilia-Romagna) as well as the Universities of Cranfield, Sheffield and Manchester in the UK are main examples of this spread of locations.
- Tier suppliers such as GKN in the UK but also Zodiac Aéro (Nord-Pas-de-Calais-Picardie), Finmeccanica Group (Piemonte/(Liguria), Safran (Ile-de-France) and AvioSpace (Piemonte) are active in this value chain.
- Airbus (incl. AvioSpace) is present in France and Italy (Midi-Pyrénées and Piemonte) but has AM activities also in Germany (Bavaria). It faces competition from Bombardier (Canada) which is active in Northern Ireland, Boeing (US) but also COMAC (China). Also Dassault plays a role in this segment (Rhône Alpes and Ile-de-France). The only Eastern European player identified so far is Skirosky, a branch of the US-based Lockheed Martin located in Poland (Masovian Voivodeship).

- Several interviewees referred to post-processing as being an area where further capabilities could be developed in Europe. "*Hot isostatic pressing*" in particular requires the development of EU capabilities. In a nutshell, it consists in the combination of heat treatment (around 1000 degrees celcius) combined with external pressure (around 2000 bars) to handle the material and make sure it is consolidated during the forming process and fix bad bonds among other things. On this particular activity, only a single provider was identified world-wide which is called Body CODE (US) and has been active for about 30 years.

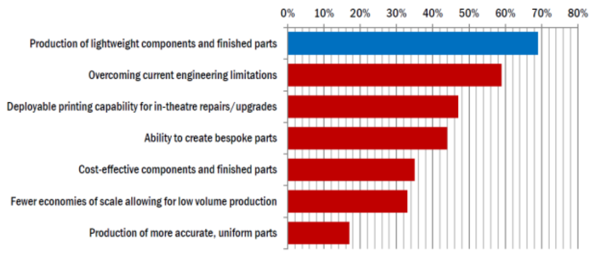
In order to summarize the critical points from the above listing, one could highlight that:

- There is a high level of **concentration of AM capabilities in Western-European regions** for this value chain, where AM is subject to a similar concentration to the one observed in the broader aeronautic value chain. Eastern European regions are therefore absent from the current value chain under the scope;
- Powder supply and in particular the supply of high-end metals does not rely on any strong player when considering transformative capabilities. While metal AM is a strength of Europe, the **transformation of key raw materials is for some of them either controlled by foreign entities or under-developped**;
- Particular **capabilities are missing** that can prove quite critical to the value chain: **hot isostatic pressing** but to a larger extent **post-processing**, finishing and post-printing treatment are under-developed. NDT (Non Destructive Testing) techniques are also a challenge, particularly for the printing of large sections. In the specific case of **wire-based technologies** the absence of **commercial systems** and **software** to enable building of parts are key missing capabilities.

(ii) Barriers to the uptake and further deployment of AM in the value chain

Figure 65 presents an expert view on some of the main technical benefits possibly drawn from AM in the A&D areas which are also found in the particular segments of civil aeronautics. One can observe that optimization is at the core of AM-related ambitions in the sector.

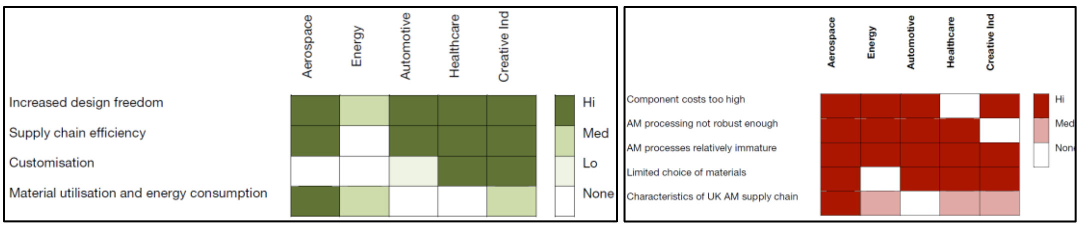
Figure 65: The key benefits of additive manufacturing over the next 10 years



Source: Defense IQ, 2016

Barriers to the uptake and further deployment of Additive Manufacturing in this value chain could also be identified during the research. They encompass some general aspects such as suggested by Figure 66 which puts in regard benefits and barriers to AM adoption. These are however observed at the sector level.

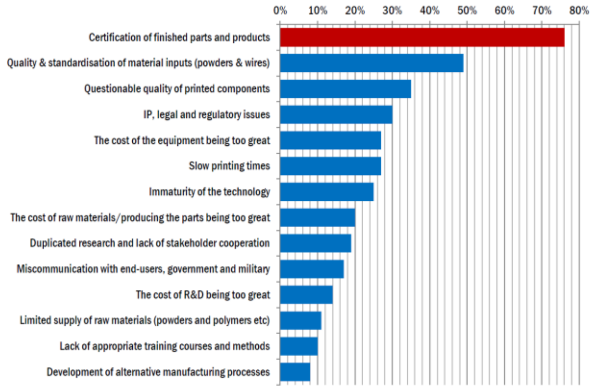
Figure 66: Generic drivers (left) and barriers (right) to AM adoption



Source: Special Interest Group Additive Manufacturing, 2012

Defense IQ (2016) clearly points at the fact that AM should become standard in the coming 20 years. It however spotted the main barriers to the advancement of AM in the fields of aerospace and Defense over the next 10 years (see Figure 67). It also refers to the fact that except for the largest players, a few companies only appear to have enough resources to steer the development and further deployment of AM. Challenges remain which are directly connected to these barriers as illustrated by Figure 67.

Figure 67: The key challenges hindering advancement of AM over the next ten years



Source: Defense IQ, 2016

Wimpenny[511] also pointed to the challenges of growing in production volume and of the need to improve AM performance, for instance in terms of operating costs. Together with the challenges identified by Defense IQ in Figure 67, these challenges are in line with the current barriers identified during the case research. Further research led to the identification of more precise barriers for this case which are listed below and for which validation was obtained during both desk and interview research processes. For Wimpenny, the current "*barriers to introduction*" facing AM are the following:

- "Concern about process robustness.
- Poor process productivity.
- Limited part size.
- Poor surface finish.
- Difficulty in conducting NDT[512].
- Need to design for AM.
- Limited range of proven material and properties"[513]

These relate to main challenges in aeronautic manufacturing, such as the one of scaling up to production volumes of thousands of parts but also of deriving methodologies to print complex thin walled parts. Other barriers could be gathered during the research process of which many echoe Wimpenny (2013). They are listed below and ordered in 5 main categories.

Value chain-specific dynamics

- **Regulatory constraints, standardization** and **certification requirements** are hampering factors to the deployment of AM in the present application area. The aeronautic value chain under the scope is clearly subject to heavy regulatory constraints that require manufacturers to meet high quality standards in a productive way. Standards have to be further developed in order to better frame design rules, margins, and other rules and characteristics to apply to AM in the area. These include in particular the process of AM, powders, monitoring modalities, severity of the defects.
- The **length of development programmes** in the sector is of key importance. The aeronautic sector is concentrated and steered by large multinational companies. The systems (aircrafts) are large and require large investments. They are also subject to many constraining validation processes (see the above standardization and certification issues) due to the fact that human lives are at stake. Therefore, investment plans and development times usually take longer than in other sectors. Development programmes in the aeronautic sector are usually planned over 50 years. This means that the current developments relate to roadmaps that were drafted 50 years ago, with limited space for shifting their focus – although these are not filters that entirely keep the industry from developing AM of course. In the area of aeronautic AM, internal technical validation, certification and production can take years. This is particularly true for structural components, especially when those are critical to the airplane. One could expect that the length of development programmes and related constraints block the development of AM. However some margin remains for incremental adoption and development of new technologies to take place. Nonetheless, these technologies that are not fully part of the development plan are therefore not yet subject to large investments and are not seen as priorities.

Knowledge

When referring to knowledge-related barriers, two sub-categories are to be referred to here: the one of skills and the one of Research and Development (R&D). Both are currently subject to important barriers that are most likely the first to be overcome to allow further deployment of AM in the area of large structural metallic components for airplanes.

[511] David Wimpenny (2013), "*Impact of Additive Manufacturing on the next generation of aircraft*", mtc – Manufacturing Technology Centre and Catapult – High Value Manufacturing
[512] It is understood by the author of this case study that NDT refers here to non-destructive testing.
[513] Source: Wimpenny, 2013

- The **lack of appropriate skills** (including ICT skills) is one of the very key barriers that has very often been mentioned as one of the most critical ones by the interviewees. One can indeed not run a 3D-Printer or organize the integration of additive manufacturing capabilities into a business unit without proper knowledge. Specialised knowledge, for instance IT-related knowledge, is still seen as a main obstacle to the deployment of AM in this value chain.
- There is a clear **need for common standards and further characterization** of the materials and processes at stake, both of which require more advanced knowledge and concertation between the actors involved. The **lack of knowledge about the technology** (mainly in terms of process and material properties) appears to be problematic.
  - Knowledge about AM **process** needs to be developed. The programming of the laser and other device settings are understood. But it is not yet fully understood how and why results are resulting from the process of melting powders with a laser. Influencing variables are not yet understood.
  - Knowledge about **materials** is also to be developed further, regarding all properties of the powders. Further knowledge would lead to progress in qualification and eventually easier certification of good quality powders.
- Beyond knowing "***how***", an interviewee from a large integrator also reffered to th0e importance of knowing "***why***". For instance, one should eventually know about the levels of oxygen that can be tolerated in the printed material to avoid failure and fracture.
- In addition, one could also mention that it is **not yet clear** what the **toxicity, explosive character** and broader **health impacts** of fine powders are. All these limitations in terms of the knowledge about the technology limit the exploitation and standardization efforts of the organisations involved. Nano-sized powders are highly volatile, even in a 3D-printer chamber, and can condensate in a room's walls.

Technology performance

Current **technological performance** is problematic as it does not yet match the existing production technologies.

- **Scalability** and more precisely the possibility to **scale up production volumes** is an issue that hampers the further development of AM and its deployment to the broader value chain. Like in other fields, AM still has to find its place in production chains as it has to compete with the cost of other available technologies. An interviewee explained that the size of EU printer manufacturers (which are usually not large multinational firms) plays an important role as these companies do not usually have enough capacity to concentrate on the development of performance features of their devices.
- Scalability also relates to **technical limitations** that require further R&D. Current powder-based AM devices for instance only allow for about 1m x 1m components[514]. Therefore, printing large components[515] still require assembly efforts. However new systems are coming out. Nonetheless flight-critical and mechanically loaded parts produced in thousands cannot be associated to any crack or mistake. Larger parts imply different stress constraints, and different non-visible parameters than smaller ones. For instance, an interviewee referred to the principle of non-linearity due to the Coefficient Thermal Expension (CTE): linearity would be lost in production when the parts produced are bigger. Aerodynamic effects require larger parts to be as good as possible. Shape acuracy for larger components is therefore currently a barrier, especially as the current powder-based technologies do not allow for printing full-size large metal components for aircrafts. On the other hand, arc and wire technologies are said to face limitations in terms of granularity of the final components printed. Larger machines that would perform better (better resolution, better replicability, better surface finishing, etc.) are therefore needed with related qualifications.
- Monitoring and control are also to be developed together with relevant knowledge of AM processes. It is particularly relevant when dealing with surfaces. All components have a surface, which needs protection, painting, will suffer from damages, but will also provide information. **Detection, monitoring and control of surfaces** is important (to detect issues for example) and **requires further development**. Developments are taking place on aspects such as temperature monitoring and control[516], but a lot remains to be done in this area and in particular when regarding surfaces.
- For the **wire based processes** and specifically WAAM the business drivers identified are cost and lead saving compared to current manufacturing method.

[514] This is not the case for wire-based technologies for which "*limitations are around residual thermal stress and management of this and distrotion for all AM techniques*" according to an interviewee.

[515] A critical factor that is technology-related links back to size limitations (interviewees usually point at a current limit of max. 1m² with EOS and SLM Solutions' systems, with larger possibilities when using ARCAM or alternative systems).

[516] Materialise in Flanders (BE) developed for instance an open-source platform to develop and make accessible a temperature control system that can ensure that the right temperatures are maintained in different areas of the printing chamber.

Missing capabilities: materials and finishing

The second phase of case study research led to a better delineation of possible missing capabilities. It was confirmed that specific capabilities were missing which are currently hampering the uptake and deployment of AM.

- **Appropriate capabilities in the field of AM materials are missing:**
  - It was understood from the above points that **materials sciences face limitations** in terms of understanding the melting of powders and wires. Materials properties and their processing should be developed. An interviewee suggested for instance to make use of "*classical analytical techinques found in Finite Element Modelling*"[517]. This suggests that not only close-to-market support is now missing, but also fundamental research. Feedback loops are therefore needed to ensure the iterations that are today difficult between the TRL 2-4 and later TRL stages[518].
  - The **access to critical materials** (powders but also wires such as titanium wires for which world-class leaders are Asia and North America[519]) is crucial. This was confirmed by several interviewees. Large providers of standard powders (nickel-based, cobalt-based and stainless steel powders for instance) are present in Europe. Many companies providing those materials are also European. The EU has however a weaker position when coming to high-end metals. Such particular types of metal are key to the value chain due to weight and temperature issues. This barrier applies to high-class, passivated clean powders, including **aluminum, magnesium and titanium**[520]. Volumes here are of importance and require appropriate (high level) volumes of **investment**.
- **Insufficient investment** in AM is a barrier that limits its deployment. Technical improvements (precision, cadence, etc.) but also demonstration are slowed down by the lack of available investments. This is particularly visible when compared to the US where 3D-printing companies (both device and service providers) manage to raise important funds from the financial community but also the government. (Complementary) Investments and funding[521] are said to be missing, not only as the raw materials available are expensive but also as AM barriers require more massive investments to take technological steps.
- **Testing** but also **finishing and post-treatment companies** are necessary to the production system. This is in particular true for **HIP** (Hot Isostatic Pressing)[522] as referred to in Section (i). In Europe, they are somehow **missing** as the only player with an apparent HIP monopoly is an US-based company. makes prices high for EU players and implies cost that hamper the further deployment of AM in the sector.
- **Quality** is also a key issue. As to illustrate this point, an interviewee explains that "the biggest challenge is consistency and quality assurance of material feedstock (wire and powder). New standards for AM material specifications need to be agreed within the AM industry".

Information and awareness

Information and awareness are necessary for two reasons: first, streamlined information is needed for any innovation system to work efficiently. Second, awareness is needed for managers to be able to overcome their own risk-avoidance behaviors.

- **Quality information** is an issue that hampers the uptake of AM.
    - One of the interviewees belonging to a large integrator mentioned that the production and manufacturing activities, even in a same group, remain very local and that **the coordination and information circulation are lacking some fluidity**. Although clear links beween regions (French and German regions in the first place, but also French and British ones), information diffusion remains a bottleneck that is clearly not problematic because of the small amount of information, but rather because of the too high amount of information from too many sources that are not "*objective*" but driven by commercial purposes (powder or printer resellers, etc.).
  - One of the interviewees also mentioned in addition to this point the fact that many discussions were taking place in **fragmented official instances** (working groups in administrations, in sectorial working groups, etc. can provide diverging outputs or at least outputs that are not in line with each other). Another interviewee referred to the multiplicity of existing roadmaps and working groups as an example of such fragmentation.
  - Finally, the need to overcome **the "3D-printing hype"** seems to be necessary to avoid disappointments: clear prospects and negative elements should according to several interviewees be better visible in that respect. In the context of the present case, this is necessary to clarify the information flowing between OEMs and integrators. This is also important as to manage expectations because there is no margin for error in the field of aeronautics due to possible liability issues.

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[517] The interviewee also added that "*Some of the large FEA software vendors are developing modelling code to replicate the effects of progressive hot melt deposition and resulting stress accumulation and distortion through solidification*"

[518] One should note that Technology Readiness Levels (or TRL) are referred here not as to consider innovation as a linear process but as to refer to different states of an idea (which can reach different levels of concretization in view of its diffusion to society through markets for instance and in the form of process, product, service, etc.)

[519] In particular countries such as China, Canada, India and the US

[520] Titanium 6.4 or titanium aluminide for instance.

[521] One of the interviewees explained for instance that R&D work has to be paid for, and that clients were therefore the ones buffering for the costs, slowing down the development and deployment of AM in the industry while public authorities could contribute to financially support new issues (such as technological development)

[522] In addition, an interviewee explained that "*Predictive process modelling is an emerging technology that requires further development to optimise on: maximising deposition rates which controlling thermal stress accumolation and resulting distortion with maximum size of defect tolerance. Hence HIP with powder*".

- Insufficient awareness about AM and its implications for the production chain blocks AM uptake and diffusion in some organisations. Interviewees pointed at a need for demonstrating the robustness of the technology to overcome cultural and managerial barriers (the latest being risk-avoiders) in EU companies. This includes large multinational firms. Managerial entrepreneurship is a key factor to overcome cultural barriers to the adoption of AM. Adopting such breakthrough technology means change that can to some extent be radical for well-established production lines.

4.2.3.4 Conclusion: opportunities for public support

The value chain under the scope is characterised by concentration effects around main OEMs and integrators that are mainly located in Western European regions from France, Germany, Italy and the UK in the first place. Missing capabilities and main barriers were identified which suggest opportunities fo public support. Also upcoming trends and possible future applications could be identified, ranging from specific components to the broad ambition (seen here as speculative) to one day print an entire airplane the way LocalMotors prints cars. Upcoming and future opportunities can be considered as development areas. AM of small components such as turbo chargers (4cm of diameter and 2cm height) is being developed, but in the context of this case study, the upcoming products are aircraft Wings and Fuselage in the first place. In a medium-range perspective, it is expected that AM could be used for mecanically loaded parts and later expend in order to integrate critical components. However, there is currently no clear evidence that these developments could effectively take place.

From the existing gaps in competencies and barriers to the uptake and deployment of AM in the area of large metal-based structural components for airplanes, policy implications were derived. Key priority action areas were identified which are the following:

1. The **access to critical materials and in particular titanium, aluminum, and to the extent necessary magnesium should be fostered by strengthening European transformative capabilities**. This implies that business support is brought by public entities which can be regional or national while the European Commission could foster the conditions for such business areas to develop. A broad range of instruments are available in that respect, from technology efficiency (R&D) support but also the setting up of relevant networked infrastructures (pilot production, demonstration, etc.).
2. The technical limitations of AM and missing knowledge imply that further **R&D** is conducted with relevant **co-investment from the public sector** (at regional, national and EU levels) for areas such as:
    a. AM processes;
    b. Quality of Material Feedstock;
    c. Material properties;
    d. Quality monitoring, control and detection systems;
    e. Toxicity, explosivity and broader health impacts of nano-sized powders;
    f. High-performance and high-volume production through AM systems;
    g. Large metal components production through accurate AM systems;
    h. When questioned about possible developments that would benefit the area, several interviewees referred to multi-material and hybrid forms of manufacturing.

    Such co-investment coult take the form of cross-regional collaborative R&D projects but also tax reduction schemes or other such financial incentive(s). For smaller players, innovation vouchers might play a relevant role too.
3. **Development of testing, finishing, post-treatment and demonstration capabilities.** These capabilities could be networked accross regions involved in the different areas under the scope from research to commercialisation, involving RTOs, companies, etc. Whether project-based or focusing on networked infrastructures, authorities could promote this area.

When researching the value chain, other action areas were identified. These took into account opportunities for joint regional support:

4. New **curricula** (regional and national levels are here concerned but the EC could still take a coordination and consultative role here) should be developed in order to foster the diffusion of relevant skills among the EU workforce;
5. Support to **streamline standardisation** efforts (EC level) is required to support the deployment of AM in the value chain. These imply that working groups at national and EU levels and across sectors should see their efforts brought together in order to advance the area in an efficient way.
6. **Information should be streamlined**. **Common norms, a common language and a common repository are still needed.** There is a role for the EC to play in terms of concentrating and crediting relevant information in order for EU players to avoid the overwhelming weight of multiple and biased information sources. A similar role could be taken up by the Commission in terms of management of expectations by providing clearer information to potential users on what AM can effectively do (or not do). A practical example of information repository could for instance be an on-line one-stop website to provide relevant information and network opportunities to AM users and providers in Europe. In practice, the EC could take the lead in setting up a one-stop website.

7. Collaborations already exist across regions but could be taken further advantage of. For instance, spill-overs from the aerospace to the energy sector were observed. And common interests are shared by sectors such as space, aeronautic, defense, and automotive industries. Therefore**, cooperation across value chains could be fostered** beyond the work of particular OEMs across sectors. Nevertheless, an interviewee from a large integrator recommended that public authorities do not push collaboration "*too much*". This recommendation was shared as to highlight that collaborative settings often do not lead to effective advances[523]. However, the example of aeronautic AM sucessfull spill-overs to the energy sector suggest that cross-value chain valorisation would benefit EU industry, another example is represented by the consideration that AM OEMs developed for the aviation industry could be commercialized – once finalized- in other sectors as for racing cars[524]. Collaborations could concretize through shared platforms, networks or collaborative projects on specific applications (structural titanium-based components for instance) or on specific processes (wire-based AM systems to produce vehicles' structural parts).
8. Finally **awareness** should be raised among potential users in order to diffuse information on the effective potential of AM and how to manage the transition to AM-based or AM-inclusive production chains. This would require organizing appropriate events on key topics to the industry in order to clarify the pros, cons and relevant development tracks that should guide the further deployment of AM in the value chain.
9. Beyond **powder-based technologies, wire-based ones** such as the ones developed by Cranfield University in the UK[525]or AITIIP in Spain[526] show relevant potential for large structural components such as airplane structural ones. Although the aforementioned systems are close to commercialisation (entering or going through a demonstration phase), there is currently no such system available on the market. Therefore there is potential for EU to take advantage of a possible market opportunity and to facilitate demonstration in this area by supporting (cross-regional) pilot production and demonstration activities.
10. The aircraft manufacturing value chain is **consumer-driven**. However, the uptake and diffusion of AM has so far mainly been driven by technology push initiatives emanating from 3D-printing suppliers (both printer and service providers) and OEMs. There is here space to influence the orientations of the value chain by **influencing demand** (at the levels of airlines and/or customers). One example is the one of regulation (whether environmental or other types of regulation) which already prove to steer changes in this value chain when oriented toward the need to optimize aircraft components.

Having discussed this issue with non-user companies, it is possible to confirm that the aspects of lack of knowledge and technical limitations of the technology are hampering the adoption of AM in the area while the other barriers mentioned in Section 4.2.2.3(ii) add to these and hamper its further deployment.

4.2.4 Inert and hard implants

4.2.4.1 Scoping

(i) Context

The application of additive manufacturing in the healthcare industry occurred for the first time in the early 2000s. First applications were dental implants and custom prosthetics[527]. Since then, additive manufacturing has evolved and becomes increasingly used. The applications in the healthcare industry have increased and improved in line with an increase in printer performance, resolution and available materials[528]. Medical applications for 3D-printing are expanding rapidly and are expected to revolutionize health care (Ventola, 2014)[529].

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523 According to this interviewee, collaborations exist and are good as they stand, but more collaboration would not lead to groundbreaking progress.

524 As per the intervention of Paolo Gennaro – AM Product leader of GE Avio during https://ec.europa.eu/jrc/en/event/workshop/paving-way-advanced-manufacturing-technology-transfer

525 See www.titanium.org/resource/resmgr/AddisonAdrianTiEU2015-3DAddi.pdf

526 See http://www.aitiip.com/en/activity-areas/mechanical-manufacturing.html

527 Gross BC, Erkal JL, Lockwood SY, et al. Evaluation of 3D-printing and its potential impact on biotechnology and the chemical sciences. Anal Chem. 2014;86(7):3240–3253.

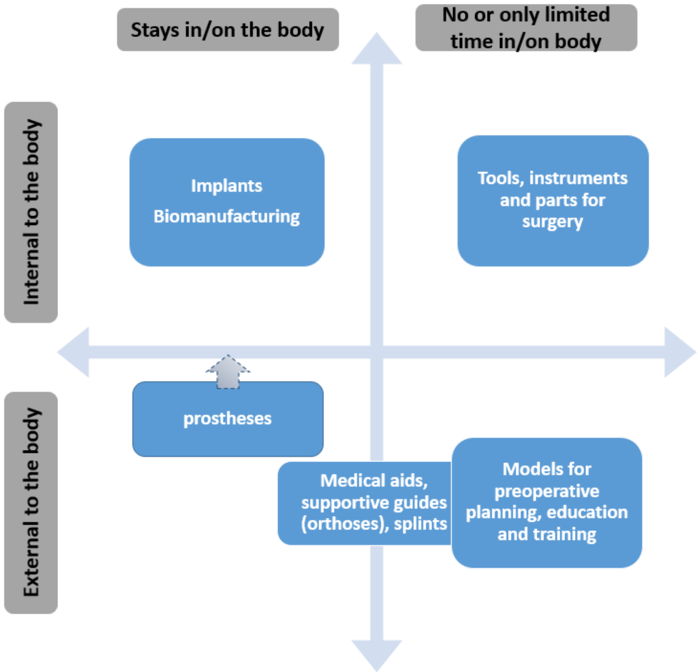
528 Gross BC, Erkal JL, Lockwood SY, et al. Evaluation of 3D-printing and its potential impact on biotechnology and the chemical sciences. Anal Chem. 2014;86(7):3240–3253.

529 Ventola, C. L. (2014). Medical Applications for 3D-printing: Current and Projected Uses. *Pharmacy and Therapeutics*, *39*(10), 704–711.

The total market for additive manufacturing in the healthcare industry was 4,1 billion dollar in 2014 and is expected to grow to 21 billion dollar in 2020 (Wohlers, 2015). The size of additive manufacturing in the healthcare industry was about 490 million in 2014 and is expected to grow 25% each year between 2015 and 2020 up to 2,13 billion dollar in 2020.[530] Literature indicates that the biomedical sector has the properties of becoming one of the most fertile fields for innovations in additive manufacturing (Ventola, 2014). Medical applications can be grouped into different categories[531] (see also Figure 68):

- Models for preoperative planning, education and training;
- Medical aids, supportive guides, splints, and prostheses;
- Tools, instruments and parts for medical devices;
- Inert implants;
- Bio manufacturing (tissue engineering and additive manufacturing).

Figure 68: Medical applications in healthcare



Source: IDEA Consult

Additive Manufacturing is well suited for the application in the healthcare sector[532], because of following reasons:

- The large market of healthcare customers;
- Several medical devices are relatively small in size which makes it possible to produce them via common additive manufacturing systems;
- Value-dense products (combining relatively high value with relatively small physical volume) with high level of customization;

Especially the option for the high level of customization was frequently indicated in the interviews as an important added value of additive manufacturing to the production of implants, as well as the possibility to manufacture implants with a complex structure. The customization of implants implies that there is no need to tailor the standard implant to the patient anatomy, and as such increases the precision and decreases the time of surgery.[533] Additive manufacturing has the advantage over traditional manufacturing that it offers the possibility to produce complex structures. The porous nature of the additive manufactured implant also allows the bone to grow into the implant which creates a natural bond.

530 http://www.fabulous.com.co/blog/2015/11/impression-3d-medecine-medical-sante-quel-marche/
531 Tuomi J, Paloheimo K, Björkstrand R, et al. Medical applications of rapid prototyping – from applications to classification. In: da Silva Bartolo PJ, Jorge MA, de Conceicao Batista F, et al. (eds). Innovation development in design and manufacturing: advanced research in virtual and rapid prototyping – Proceedings of VR@P4, Leiria, Protugal, October 2009, pp. 701-704. Boca Raton, FL: CRC press.
532 3D opportunity in medical technology: additive manufacturing comes to life. Deloitte University Press, 2014.
533 Additive manufacturing for personalized knee systems. Driving better outcomes for patients as well as healthcare providers. White paper 2014, Cyient.

Ventole (2014) identified several benefits of 3D-printing application in healthcare:

- One of the greatest advantages of additive manufacturing in medical application is the option of customization and personalization of medical products, drugs, and equipment. This can create great value for both the patient and the physicians[534].
- Another benefit is the increased cost-efficiency. For large-scale production, the traditional manufacturing methods are still less expensive but for small scale production, additive manufacturing becomes more and more competitive. The application of additive manufacturing is especially advantageous for low production volumes and/or complex applications[535,536].
- Traditional manufacturing methods require milling, forging and a long delivery time for making an implant. Additive manufacturing enhances productivity in that often a product can be made in a couple of hours[537]. Also resolution, accuracy, reliability and repeatability of 3D-printing technologies are improving[538].
- The democratization of the design and manufacturing of goods is also beneficial for the application of 3D-printing in medicine.[539]

(ii) Application area: Inert and hard implants

During the first phase of the study, the area entitled "Inert implants, hard implants i.e. bone replacement (e.g. acetabular implants, skull implants, sternum implants)" was selected. The choice to include this application was based on the fact that it is a B2B and B2C market which is already relatively mature (varying from close-to-market to on-market) and has a growing market expectation as it is identified as an "innovative emerging industry". Wohlers (2015) estimates that the Food and Drug Administration (FDA) has already provided clearance for more than 20 different additive manufacturing medical implants. It concerns, among others, cranial implants, hip, knee and spinal implants. Of the acetabular (hip cup) implants, already 100,000 units have been produced, of which about 50,000 have been implanted into patients (Wohlers, 2015).

Extensive web-based searches and interviews led to the identification of a number of cases where additive manufacturing was used for printing implants. In order to delineate the scope of the application area, the main application areas of implants were explored in order to identify possible leading products.

1. Type of implants

The market for 3D-printed hard and inert implant applications can be segmented as follows[540]: Orthopedic, cranio-maxillofacial and dental implants. In the following sections, these three groups of inert and hard implants are discussed more in detail.

- Orthopedic and spinal implants

An orthopedic implant is a device surgically placed into the body designed to restore function by replacing or reinforcing a damaged structure. There are different types of orthopedic implants: Hip, should and knee.

Currently, hip replacements is a frequently occurring surgery. A hip implant consists of the following three parts: the acetabular cup, the femoral component, and the articular interface. An already frequently produced implant is the acetabular cup (see Figure 69). The acetabular cup is placed in the hip socket (acetabulum). The lattice structure improves osseointegration[541]. Also knee and shoulder implants can and are already manufactured with additive manufacturing technology.

534 Banks J. Adding value in additive manufacturing: Researchers in the United Kingdom and Europe look to 3D-printing for customization. *IEEE Pulse* 2013;4(6):22–26.

535 Schubert C. van Langeveld MC, Donose LA. Innovations in 3D-printing: a 3D overview from optics to organs. Br J Ophtalmol 2014; 98(2): 159-161.

536 Mertz L. Dream it, design it, print it in 3-D: What can 3-D printing do for you? *IEEE Pulse* 2013;4(6):15–21.

537 Gross BC, Erkal JL, Lockwood SY, et al. Evaluation of 3D-printing and its potential impact on biotechnology and the chemical sciences. Anal Chem. 2014;86(7):3240–3253.

538 Banks J. Adding value in additive manufacturing: Researchers in the United Kingdom and Europe look to 3D-printing for customization. *IEEE Pulse* 2013;4(6):22–26.

539 Mertz L. Dream it, design it, print it in 3-D: What can 3-D printing do for you? *IEEE Pulse* 2013;4(6):15–21.

540 http://www.transparencymarketresearch.com/3d-Printing-medical-applications.html

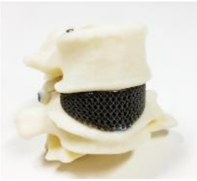
541 https://scrivito-public-cdn.s3-eu-west-1.amazonaws.com/eos/public/b674141e654eb94c/c5240ec3f487106801eb6963b578f75e/medicalbrochure.pdf

Figure 69: Acetabular cup with lattice structure

Source: Arcam

There are also some examples of 3D-printed spinal implants. An example is the intervertebral fusion cage, which is a spacer that is implanted between two vertebrae hollow cylinder (see Figure 70). The holes in the cage keep the graft in contact with the bony surface of your vertebrae. This ensures that the bone graft unites with the vertebrae, forming a solid fusion[542].

Figure 70: 3D-printed intervertebral cage



Source: RMIT University543

- Cranio-maxillofacial implants

Cranio-maxillofacial is the anatomical area which covers the skulls, face, mouth and jaws. Cranio-maxillofacial surgery refers to a procedure used for the treatment of severely injured cranial or facial bones[544]. Cranio-maxillofacial implants are thus used for facial and skull reconstructions. Figure 71 gives an example of a customized skull implant positioned on a medical model, indicating how it will be applied to the patient. Figure 71

Also medical/surgical meshes, *a medical device that is used to provide additional support to weakened or damaged tissue*[545] can be manufactured via additive manufacturing technology.

Figure 71: Custom cranio-Maxillofacial implant

Source: Arcam[546]

542 https://www.depuysynthes.com/patients/aabp/resources/articles_learn/id_86
543 https://www.rmit.edu.au/news/all-news/2015/august/australias-first-3d-printed-spine-implant/
544 Transparancy market Research: Press Releases http://www.transparencymarketresearch.com/pressrelease/craniomaxillofacial-implants-market.htm
545 http://www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/ImplantsandProsthetics/HerniaSurgicalMesh/default.htm
546 http://www.arcam.com/solutions/orthopedic-implants/

- Dental

Also dental implants are hard/inert implants. They were in the first stage of the analysis excluded as focus area as the market for dental implants is considered to be rather mature. EOS indicates that their additive manufacturing equipment already produces more than 5 million metal copings, which are used to produce crowns and bridges, every year (Wohlers, 2015).

The focus of this case will therefore be on the orthopedic implants and the cranio-maxillofacial implants.

2. Material

There are different categories of additive materials: polymers, metals, ceramics and biological cells. Overall, the two major categories of additive materials are polymers and metals (Wohlers, 2015).

As with many applications of additive manufacturing, also in the healthcare sector, the materials are important. There is a growing trend toward making 3D-printed implants out of a variety of metals and polymers, which are also in the healthcare sector the major categories of materials used.

- Metal

According to Leandri (2015), "*Preferred materials for the fabrication of implants are pure titanium and Ti6Al4V alloy. Pure titanium possesses a higher resistance to corrosion and is considered the most biocompatible metal. It spontaneously forms a stable and inert oxide layer as soon as its surface is exposed to an oxidizing media. If a higher strength is required in the biomedical implant, then a better choice is the Ti6Al4V alloy, which also exhibits good resistance to fatigue and corrosion with a low specific weight.*

Other biocompatible materials available in powder form are stainless steel 316L and cobalt-chrome alloys. The highly controlled ALM atmosphere (neutral gases and restricted oxygen) ensures the high purity of the printed parts and preserves the expected material properties".[547]

- Polymer

The Additive Manufacturing of plastic products can make use of polyamides (PA), polystyrenes (PS), thermoplastic elastomers (TPE), and polyaryletherketones (PAEK).[548] Specifically for the healthcare sector, PAEK is used (see box 1).

Box 41: PAEK, PEEK

Polyaryletherketones (PAEKs) are since the 1980's more and more applied as biomaterials for among others orthopedic and spinal implants. Family of PAEK is PEEK; polyetheretherketone. PEEK is resistant to simulated in vivo degradation, including damage caused by liquid exposure. [549] *"Parts created with PEEK are compliant with FAR 25.853 and UL 94 V0, and have very good chemical and hydrolysis resistance. PEEK parts exhibit high potential for biocompatibility, can be sterilized for medical applications, and are lightweight with high wear resistance.*[550] This makes PEEK a good material for medical instrument parts. It was offered commercially as biomaterial for implants for the first time in 1998. PEEK materials are also being used for additive manufacturing. There are still some technical limitations towards the large scale use of PEEK material for additive manufacturing as currently, there are only a limited amount of SLS machines which are able to use the material for AM.[551]

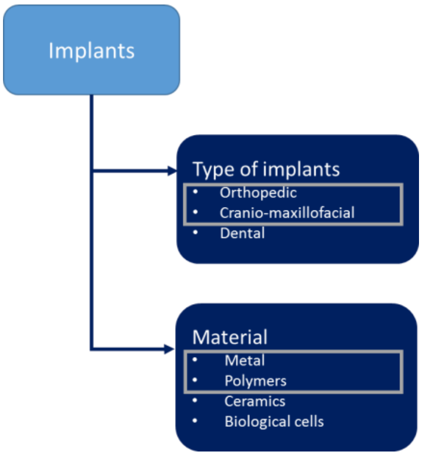
- Ceramics

Research towards the use of ceramics in additive manufacturing for medical devices has recently increased. Ceramics is not a new material but the way of producing it has changed. The combination of ceramics with additive manufacturing technology allows to produce implants with a high porosity and a very high accuracy. Ceramics has some strong commercial potential. Up to now, there are is only one 3D-system provider of printers which can use ceramics (Prodways in France). Companies who produce ceramic implants at the moment are using adjusted commercial printers to do this.

The approach selected in this case study is to emphasize the dominant products that have a high TRL. We focus on inert and hard implants manufactured from polymers and metals. Taking into account the maturity level of the application, dental implants (already very mature), as well as implants in biodegradable material and ceramics and bio printing (still premature) are excluded.(see also Figure 72 for the scope of this case on inert and hard implants).

547 http://3dprint.com/52354/3d-print-medical-implants/
548 http://www.eos.info/material-p
549 Kurtz, S.M. and J.N. Devine (2007) PEEK materials in Trauma, Orthopedic and spinal implants. Biomaterials; 28(32): 4845-4869.
550 http://www.industrial-lasers.com/articles/2013/04/3d-printing-of-peek-expands-options-for-additive-manufacturing-i.html
551 https://www.nae.edu/Publications/Bridge/57865/58467.aspx

Figure 72: Scope of this case



4.2.4.2 Identifying value chain components

(i) Identification of key players and usage of Additive Manufacturing

Inert or hard implants manufactured by 3D-printing are already on the market and sold by different types of companies. As indicated, the focus is on two segments where 3D-printing technology is used to produce implants: orthopedics and cranio-maxillofacial. Important players in the market for the production of 3D-printers are 3Dsystems (US), Stratasys (IL), EnvisionTEC (DE), and Arcam (SE). Some of these companies are also service providers (e.g. 3Dsystems via Layerwise). There are different examples of successful production and use of implants as discussed below.

Orthopedic implants

From the different type of implants, the hip, knee and shoulder are implants which are already frequently produced using additive manufacturing technology (see also section 1.2). One of the main advantages of additive manufacturing of implants is the possibility to produce complex structures and the ability to customize implants. The ability to produce customized implants is important in orthopedics as surgeons do not need to perform bone graft surgeries or use scalpels and drills to make the implant fit. Especially in complex cases, customized implants add a lot of value (Ventole, 2014). Customization of the additive manufactured implants used to be the only way to be cost competitive relative to the implants produced by traditional manufacturing. There are different companies who are targeting this customized implants market e.g. Mobelife (BE). A Swedish teenage girl, with a deformed hip joint, received a hip implant which allows her to walk again without crutches. This surgery made use of the virtual planning of Materialise's Mimics and 3-matic software and the 3D-printed implant produced by Mobelife[552]. Mobelife also contributed to a ground-breaking new hip surgery carried out at Norwich hospital (UK)[553], where the patient lost a staggering amount of bone which meant that a hip reconstruction was not possible. "*The company created an implant made of trabecular metal (a mix of spongy tissue and adult bone) and then tested by being inserted into a plastic copy of the patient's pelvis. After the operation the patient's bone will grow into the porous implant, which means the new hip should last the patient's lifetime".*[554] Other important players which focus on the customized implants market are e.g. Xilloc (Nl). Companies have been able to improve the production process of additive manufacturing e.g. the cost of material, production, scanning techniques etc. has improved. This allows companies such as Arcam and Layerwise (3Dsystems) to currently produce implants on a large scale.

Also in spinal surgery there are some examples of the use of 3D-printed implants. In France in 2014, a surgeon performed the world's first spinal-fusion surgery to correct a patient's severe spinal deformities. "*During the surgery, Dr. Fiere replaced discs that were damaged with spinal cages to separate the vertebrae and align the spine. He then inserted a curved spinal rod to help maintain the new alignment. The intersomatic cage, specifically 'printed' for the patient, positioned itself automatically in the natural space between the vertebrae and molded ideally with the spine by joining intimately with the end plates, despite their relative asymmetry and irregularity*". The intersomatic cage that was used, was printed by Medicrea, a French company that specializes in the design, development, manufacturing and distribution of orthopedic implants dedicated to spinal surgery.[555] Anatomics, an Australian based medical device specialist, collaborated with RMIT's centre for additive manufacturing to design and develop a custom-made titanium spinal implant using additive manufacturing.

552 http://biomedical.materialise.com/cases/3d-printed-hip-puts-teenager-back-her-feet
553 http://www.mobelife.be/item/ground-breaking-new-hip-surgery-carried-out-at-norwich-hospital
554 http://www.edp24.co.uk/news/health/ground_breaking_new_hip_surgery_carried_out_at_norwich_hospital_1_4199676
555 http://3dprint.com/8821/3d-print-spinal-cage/

Prof. Brandt from RMIT indicated that "*An advantage of 3D-printing is that a custom implant can be made of any shape and complex internal architecture for a reasonable cost*"[556].

In China the world's first 3D-printed vertebrae were implanted in 2014. The results of the clinical trials of these implanted vertebrae have been promising so far. The material used for this implant is titanium powder. The added value of additive manufacturing with this implant is the shape that can be printed. This makes it easier for the implant to stay in place, without the need of additional hardware which is often required to keep generic implants in place. The porous nature of the additive manufactured implant also allows the bone to grow into the implant which creates a natural bond. [557]

Cranio-maxillofacial implants

Also in cranio-maxillofacial applications, customization of implants is important, as a skull has an irregular shape and size where standardized implants are not applicable (Ventole, 2014). A research team at the BIOMED Research Institute in Belgium has create in 2012 the method behind the first customized 3D-printed lower jaw and has successfully implanted the first 3D-printed titanium mandibular prosthesis.[558] Oxford Performance Materials received FDA approval in 2013 for a 3D-printed polyetherketoneketone (PEKK) skull implant, which was first successfully implanted that year.[559] A team of Dutch surgeons at the University Medical Center in Utrecht completed in 2014 the first complete skull transplant by replacing a woman's skull with a customized printed implant made from plastic[560]. There are also some example cases from China. In 2014, a man with a crushed skull was given a tailor-made, 3D-printed, titanium replacement[561] and in 2015, a 3-year old child which had an extremely large head received a skull replacement[562].

In 2014, a Slovak man's face was restored with EU-approved 3D-printed cranial implant. "*The Slovakian company CEIT Biomedical Engineering, a spin-off company of the Technical University of Košice, …, performs extensive research on patient-specific, lower-cost cranial implants and has now obtained EU-approval for its implant printing process. CEIT Biomedical Engineering used the Mimics Innovation Suite to convert the patient's medical scans into a 3D model. They used the software to mirror the healthy side of the skull and design a perfectly fitting implant directly on the patient's anatomy. This exact fit is extremely important for long-term success and comfort. The resulting plate was exported for 3D-printing in a biocompatible titanium alloy using Direct Metal Laser Sintering technology.*"[563]

(ii) Composition of the value chain

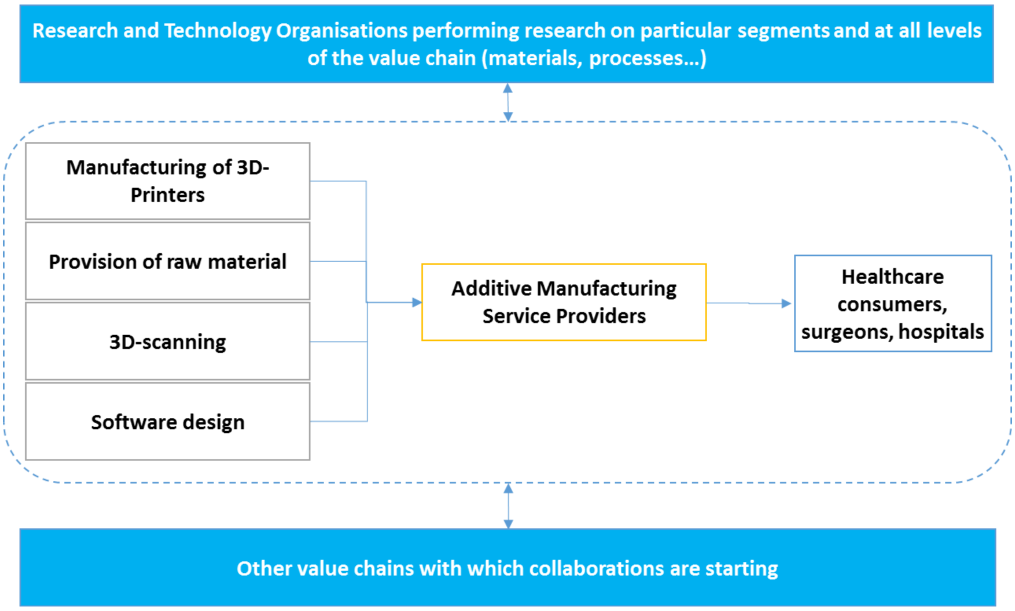
In order to understand the status of additive manufacturing in the hard and inert implant industry, the value chain is constructed positioning the key actors that are active in and outside Europe.

In Europe, the important actors involved in additive manufacturing of implants are mainly located in EU15. There have been some actors identified in Eastern Europe, but according to interviews these actors are not on the forefront of research and development. Eastern European actors are often actors involved in only one segment of the value chain whereas for example several companies in EU15 are involved in multiple segments of the value chain. A detailed list of the players is provided in Annex (section 13).

Figure 73 illustrates the main components of the inert/hard implant value chain seen through an additive manufacturing perspective. Compared to the value chain in other sectors, an additional segment is added: 3D-scanning. CT and MRI are very important for the design stage of the implants.

556 https://www.rmit.edu.au/news/all-news/2015/august/australias-first-3d-printed-spine-implant/
557 http://3dprint.com/12253/3d-printed-vertebra/
558 http://www.uhasselt.be/UH/Tijdschriften/ToonPersmededeling.html?i=482
559 Klein GT, Lu Y, Wang MY. 3D-printing and neurosurgery—ready for prime time? World Neurosurg. 2013;80(3–4):233–235
560 http://www.medicaldaily.com/breakthrough-surgeons-use-3-d-printing-technology-perform-worlds-first-skull-transplant-273288
561 http://3dprintingindustry.com/2014/08/29/chinese-farmers-skull-restored-3d-printed-titanium-mesh/
562 http://3dprint.com/81815/3d-printed-skull/
563 http://biomedical.materialise.com/blog/slovak-mans-face-restored-eu-approved-3d-printed-cranial-implant

Figure 73: Main segments of the hard and inert implant additive manufacturing value chain



Manufacturing of 3D-Printers

There are some large 3D-printer/system providers such as EOS (DE), Layerwise (BE), Arcam (SE), EnvisionTEC (DE) and Renishaw (UK) which produce 3D-printers. Some companies use them to produce implants, while others provide them to AM service providers. There are some important non-EU providers in the healthcare sector such as 3Dsystems (US) and Stratasys (IL).

An overview of the activities, the applications and the industry/market of some key 3D-system/service providers is provided in Table 31 and Table 32.

Table 31: Overview of European companies

Company	Activities	Healthcare applications:	Industry and markets
Materialise (BE)[564]	▸ Biomedical engineering software and services (Mimics Innovation Suite) ▸ Services/solutions	▸ Orthopedic implants ▸ Cranio-maxillofacial implants, mandible and mid-face reconstruction. ▸ Surgical guides	▸ Healthcare ▸ Consumer goods
EnvisionTec (DE)[565]	▸ 3D-printers ▸ 3D-printing materials	▸ (hearing aids) ▸ (dental: crowns and bridges) But no own production (some small series or prototyping)	Aerospace, Architecture, Automotive, Bio fabrication and medical, Consumer goods, Dental, Education, Electronics, Entertainment, Hearing aids, Jewelry, Manufacturing, Orthodontics, Sporting goods, Toys
Arcam (SE)	▸ 3D-printers ▸ 3D-printing materials ▸ Service and application support	▸ Orthopedic implants ▸ Trabecular Structures and cranio-maxillofacial implants	▸ Aerospace ▸ Medical
EOS (DE)	▸ 3D-printers ▸ 3D-printing material ▸ Software ▸ Services ▸ Consulting	▸ Offers additive manufacturing solutions for orthopedic applications which are tailor-made and ▸ Flexible and precision-fit cranial implants. But no own production (some small series or prototyping)	Aerospace, Automotive, Industry, Lifestyle, Medical, Tooling, Rapid prototyping,

564 http://www.materialise.com/products-and-services/products-and-services-for-medical-professionals-0
565 http://envisiontec.com/

Table 32: Overview of non-European companies

Company	Activities	Applications	Industry and markets
Stratasys (IL)[566]	▶ 3D-printers ▶ 3D-printing materials ▶ Services ▶ Medical-industry expertise	▶ Surgical guides ▶ Prototypes ▶ Custom devices	Aerospace, Architecture, Automotive, commercial products, consumer products, defense, dental, education, entertainment, medical
3Dsystems (US) [567]	▶ 3D-printers ▶ 3D-printer material ▶ Software (scanners) ▶ Services	End-to-end Digital Thread for Personalized Surgery. Digital surgical tools include: ▶ 3D-printed anatomical models; ▶ Virtual reality simulators; ▶ Direct metal printing for implants and instrumentation (orthopedic, spinal, CMF, dental); ▶ Personalized 3D-printed surgical guides.	Aerospace/defense, architecture/geo, Arts/entertainment, Automotive, Culinary, Education, Energy, Healthcare, Hobbyist, Jewelry.

Provision of raw material

The materials are provided by companies specializing in different areas. In the field of implants, this material entails metal, plastics, ceramics and biological cells. The use of these last two materials for additive manufacturing are still in an exploratory stage and are thus not included in the overview. Important for the production of implants is the biocompatibility of the material.

- Metal

There are some important material providers of metal powders[568]. Arcam (SE) provides Titanium Ti6AI4V, Titanium Ti6AI4V ELI, Titanium Grade 2, Cobalt- Chrome, ASTM F75[569] which can be used for the AM process EBM. EOS (DE) provides CobaltChrome MP1, StainlessSteel GP1, PH1 and 316L, Titanium Ti64 - Ti6AI4V, Titanium Ti64ELI[570] which can be used for SLM. And Optemec (US) is a large provider of Cobalt Satellite 21, Titanium 6-4 and 6-2-4-2, stainless steel 316 i[571] used for LDM/LENS.

- Polymer

The Additive Manufacturing of plastic products can make use of polyamides (PA), polystyrenes (PS), thermoplastic elastomers (TPE), and polyaryletherketones (PAEK).[572] EOS (DE) and Stratasys (IL) are important material provders of polymer powders[573]. EOS (DE) is a large provider of PEEK HP3 – polyaryletherketoneused with SLS AM processes[574]. Stratasys (IL) is a provider of ABS-M30i for FDM processes[575].
Oxford Performance Materials produces polyetherketoneketone (PEKK) but does not sell the powder as they produce their own biomedical devices (Wohlers, 2015)

3D-scanning

The developments taking place in 3D scanning technologies make new evolutions in the healthcare sector possible. For the replication of a bone structure, the CT (computed tomography) scan is used most frequently. Also cone-beam computed tomography (CBCT) is used in the healthcare sector but rather in the dental field. For soft tissue structures and cartilage, magnetic resonance imaging (MRI) is often applied. MRI is however less suited for bone imaging (Wholers, 2015).

566 http://www.stratasys.com/industries/medical
567 http://www.3dsystems.com/solutions/healthcare
568 Nanna Guo and Ming, C.L. (2013). Additive manufacturing: technology, applications and research needs. Front. Mech. Eng., 8(3): 215-243.
569 http://www.arcam.com/technology/products/metal-powders/
570 http://www.eos.info/material-m
571 http://www.optomec.com/3d-printed-metals/lens-materials/
572 http://www.eos.info/material-p
573 Nanna Guo and Ming, C.L. (2013). Additive manufacturing: technology, applications and research needs. Front. Mech. Eng., 8(3): 215-243.
574 http://www.eos.info/material-p
575 http://www.stratasys.com/materials/fdm/abs-m30i

Software design

To transform the medical image data produced by CT scans (2D images to 2,5 or pseudo-3D by using a "slicing technique"), specialized software is needed. The most common format of medical imaging is DICOM, an open-source standard. In addition, it is necessary to export the medical image data to a suitable additive process format (STL) (Wohlers, 2015).

Some important actors in the software design segment are not focused on the healthcare sector alone and are central providers on the market e.g. Materialise and 3Dsystems. Specifically for applications in the healthcare sector there are image-processing software products (see Table 33).

Table 33: Overview of medical image-processing software products

Product	Manu-facturer	Country	Description
Mimics	Materialise	Belgium	Imports from various medical-imaging modalities, processing the images, and exports to STL and native additive-manufacturing formats
3Matic	Materialise	Belgium	Allows for digital design by manipulation of STL files: useful in design and manufacture of complex prosthetic devices
RapidForm	3D Systems	United States	Imports DICOM image data, processes the images, and exports to various formats
Amira	Vision Imaging	France and Germany	Imports from various medical-imaging modalities, processes the images, and exports to STL format
Osirix	Open Source	Switzerland	Imports from various medical-imaging modalities, processes the images, and exports to STL format: allows for image fusion between different scan types
Geomagic Studio	3D Systems	United States	Imports CBCT images and provides tools for the design of dental-related prosthetics.

Source: *http://www.wohlersassociates.com/medical2015.pdf*

Additive Manufacturing Service Providers

An additive manufacturing service provider is a company which provides additive manufactured implants and services to their customers. Three different types of additive manufacturing service providers in the field of hard and inert implants can be distinguished.

- There are some companies which are historically the main providers of implants; e.g. some large orthopedic companies. These companies combine traditional manufacturing and additive manufacturing. Some big players are Johnson and Johnson (US), Stryker (US) and Zimmer Biomed (CH). Other companies are Oxford Performance Materials (US), Smith and Nephews (US)[576] and Medacta (CH). The follow the trend, but are not often at the forefront of new technological developments related to 3D-printing in the healthcare sector. They often focus on larger scale production of 3D-printed implants, as this fits better to their business model.
- There are also some companies, often smaller in size, which focus on the customized implant market. An example is Xilloc (Nl). They provides services most of the time directly to hospitals. Sometimes they provides services to other AM service providers.
- There are also companies which focus on additive manufacturing technology and provide services in different industries: Materialise[577] via Mobelife (BE), EOS (DE), 3D systems (US) (via Layerwise,BE), Renishaw (UK), Stratasys (IL), Arcam (SE). Additive manufacturing system manufacturers which also operate as service providers, sometimes do this via an acquisition strategy, e.g. Layerwise is acquired by 3D systems (Wohlers, 2015).

Healthcare customers, surgeons and hospitals

The implants are provide to the hospitals where the surgeons implant them in a patient. During the interviews it was indicated that the surgeon plays an important role in the choice of implants: traditionally manufactured versus additive manufactured implants. At the moment, a lot of surgeons still prefer to work with traditionally manufactured implants. It is important to inform surgeons about the different options of implants. Customized implants allow for less adjustments of the implant during surgery and less follow-up surgeries. This reduces the surgery time, which is beneficial for the patient. Overall the cost aspects seems to be an issue for the hospitals. An interviewee made the remark that hospitals have different budget divisions: a surgical division which performs the surgery and an implant purchase division. The customized 3D-printed implant might indeed be more expensive, but the reduced surgery time and the related benefits for the patient might cover for this additional cost.

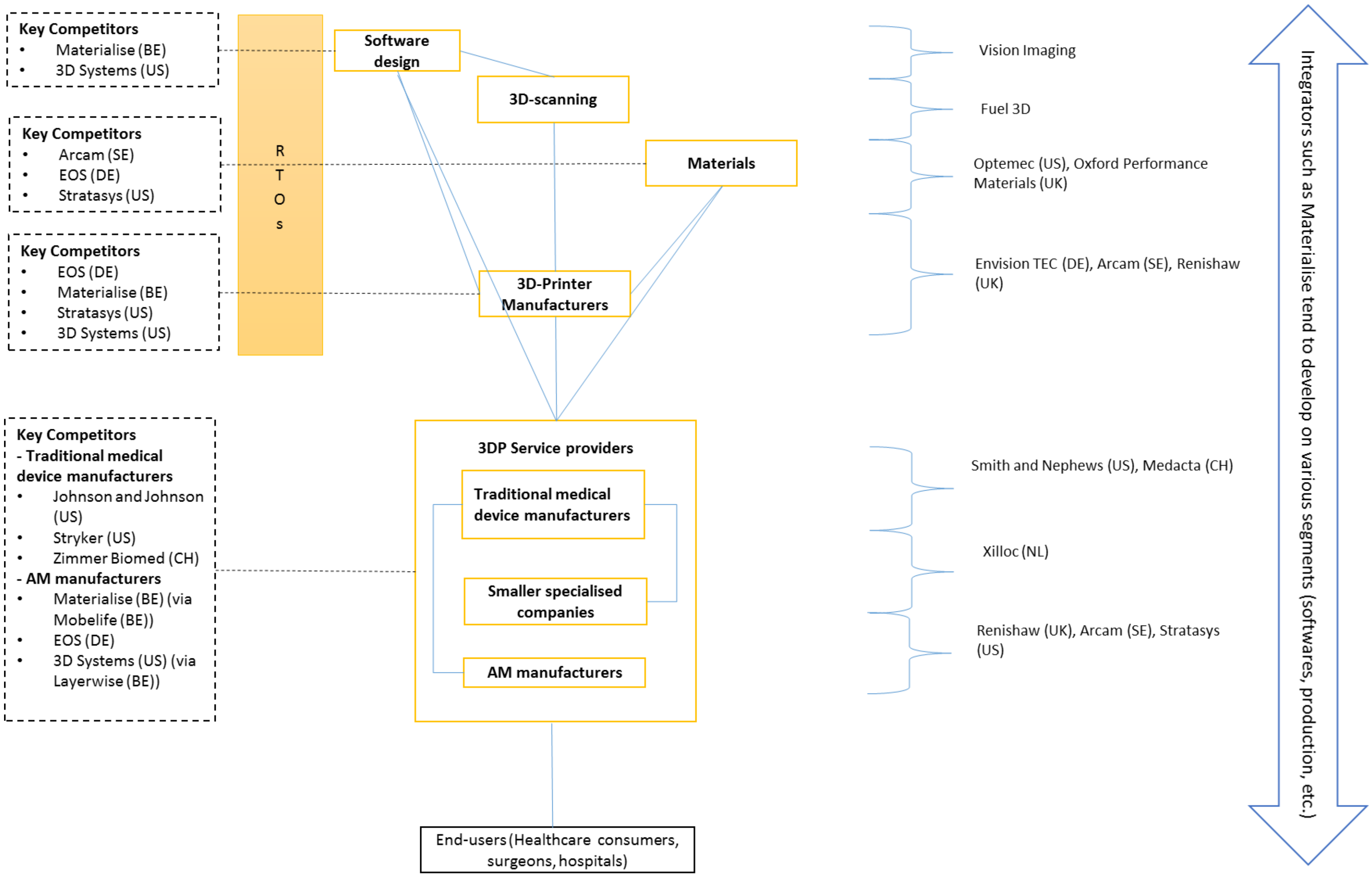
576 http://www.smith-nephew.com/about-us/what-we-do/orthopaedic-reconstruction/

577 3D-printing in medical applications market (medical implants, surgical guides, surgical instruments, bio-engineered products) – global industry analysis, size, share, growth, trends and forecast. Transparency Market Research. September 15th, 2015.

Research and Technology Organisations
RTO actors are quite active in the field of additive manufacturing in medical devices (including implants). New developments of Additive Manufacturing in healthcare often happens in collaboration with RTO's and industry. Some important RTO players are identified in the UK (NewCastle University, Warwick University, Loughborough university, Nottingham University), Belgium (KU Leuven) and Germany, but also in other European countries like Italy, Spain, France etc. Limited activities seems to take place in Eastern European RTO's. Research often consists of collaboration between engineers, surgeons and radiologists. Research also occurs at different segments: material, medical imaging as well as 3D-printers.

Connections with other value chains
As indicated, there are some companies which focus on additive manufacturing technology and provide services to different industries like aerospace, healthcare, automotive etc. In this way, there is some interconnectivity between different industries such as e.g. manufacturing, consumer products, healthcare etc. Some collaboration might occur between the healthcare industry and the aerospace industry, this mainly for the materials for additive manufacturing. Aerospace industry does perform research on the strength of materials (i.e. PAEK) which is also relevant for the healthcare industry.

Figure 74: Illustration of the (hard/inert) implants additive manufacturing value chain



(iii) Functioning of the value chain and critical factors

Deloitte and Medtec (2015)[578] constructed a framework in which they present th**e impact of additive manufacturing on industry** (also discussed in the case "surgical planning"). Additive manufacturing makes it possible to break existing performance trade-offs in two fundamentals ways:

- Additive manufacturing reduces the capital required to achieve economies of scale: less capital is required to reach minimum efficient scale for production, lowering the barriers to entry to manufacturing for a given location. This shapes the **supply chain**.
- Additive manufacturing increases the flexibility and reduces the capital required to achieve scope: more variety of products per unit of capital can be produced, reducing the cost of production changeovers and customization and the overall capital required. This shapes the **product (design)**.

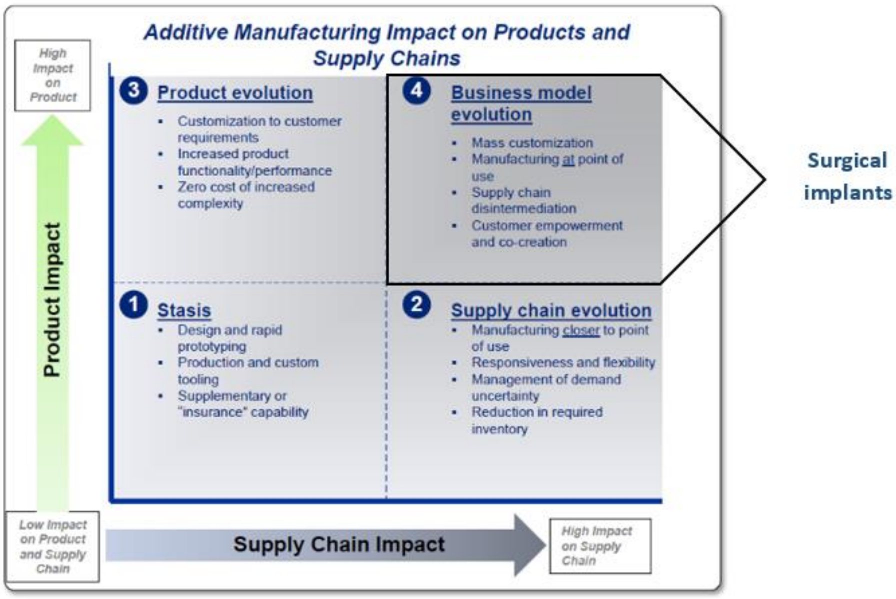
The framework outlines four tactical paths that companies can take when wanting to improve product and/or supply chain competitiveness via the use of additive manufacturing technologies. The paths take into account the capital versus scale and scope relationship, and as such distinguish between the product and supply chain impact.

Path 1: Companies want to improve performance without alternations in supply chains or products;
Path 2: Companies want to improve performance via alternations in supply chain but not in products;
Path 3: Companies want to improve performance via alternations in products but not in supply chains;
Path 4: Companies want to improve performance via alternations in both products and supply chains.

Using additive manufacturing technology for implants has an impact on the competitiveness of the supply chain and the product chain and can induce the following changes relevant for this case on "hard and inert implants" (see also Figure 75):

- Lower cost due to mass customization (product chain);
- Better fit due to mass customization (product chain).
- Inventory reduction due to on-site production (supply chain);
- Improved performance due to on-site production (supply chain);

Figure 75: How will additive manufacturing impact industry



Source: Deloitte Services LP. 2015

These possible changes in the supply chain might have an impact on the value chain, which will be explored in the second phase. Especially the item on "on-site product customization" is necessary to analyse in further detail. According to some interviewees, hospitals might be reluctant to produce implants in-house. The in-house production of implants requires the availability of different types of skills; not only surgeons and radiologist are involved, but also engineers with experience with computer aided design, additive manufacturing process and materials are important. The engineering skills are currently still lacking in hospitals.

578 3D opportunity in medical technology: additive manufacturing comes to life. Presentation by Dr. Mark J. Cotteleer, 22 April 2015.

Other items in the supply chain which can influence the value chain and therefore need to be further explored are (Deloitte, 2014):

- Are there suppliers that are developing additive manufacturing competences?
- Is there a possibility of coproduction with suppliers and customers?

4.2.4.3 Missing capabilities

(i) Regional dimension

The key markets in global 3D-printing in medical applications are Europe, North America and Asia Pacific. According to Transparence Market Research (2015), North America was the dominant market in 2012. According to them, the economic conditions in Europe are more conductive, stimulating market growth, and possibly allowing Europe to surpass North America by 2019[579].

Looking at the regional dimension of the case study "inert and hard implants", one can notice that the existing capabilities are concentrated in Western European countries and some links can be observed between the players at stake or the regions from which they operate. Based on the desk research and interviews performed, we have not been able to identify key players in the Eastern part of Europe.

Belgium has had a pioneering position in additive manufacturing since the 1990s[580]. The number of companies that enters the additive manufacturing market is growing and existing companies also explore the possible use of additive manufacturing for traditionally produce products.

- Sirris, a collective centre for the technological industry has 25 years of experience with additive manufacturing in material and production methods. It comprises 140 technology experts spread over 7 sites in Belgium, serving 5000 customers of which 80% SMEs.[581]
- KULeuven, department of Mechanical engineering, is mainly performing research on stereolithography (SLA) and selective laser sintering and melting (SLS/SLM). "A patented SLA liquid curtain recoating system has reduced the time needed for depositing successive liquid layers by a factor of ten, yielding a proportional reduction in production time. Major advances are made in direct laser sintering of high strength metal powders like steel, titanium, tungsten carbide and other materials. The application of these material addition processes to actual manufacturing (so- called Rapid Manufacturing) is mainly focusing on tool manufacturing (Rapid Tooling), aerospace manufacturing (a/o production of light-weight hollow structures) and medical prostheses (dental prostheses, scaffolds). A major break-through has been achieved in rapid manufacturing by moving from SLS to SLM".[582]
- Materialise is a spin-off of KU Leuven and is market leader in additive manufacturing software and solutions. It offers patient-specific or customer-specific solutions such as surgical guides. Mobelife NV, also located in Flanders, is part of Materialise's medical applications. Mobelife offers a completely customized product development process for patient-specific orthopedic implants.[583]
- Mobelife was founded as part of the Materialise Group and is active since 1990. As an integral part of Materialise's medical applications, Mobelife's servs and assist health care providers directly – and patients indirectly – by a completely customized product development process for patient-specific orthopedic implants.[584]
- Layerwise is a spin-off of KU Leuven and is now part of 3Dsystems. It focusses exclusively on additive manufacturing of metal parts (Direct Metal Printing, DPM) and invests a lot in R&D to push the boundaries of additive manufacturing. It targets serial production and prototyping. Layerwise provides instrumentation used for orthopaedic, spinal and cranio-maxillofacial applications.

During the interviews and desk research, other regions are identified (see also case "surgical planning").

- In **Asturias (Spain)**, there is a cluster on additive manufacturing and different companies active in the healthcare sector (focusing on implants) are involved. Prodintec is a technology centre specialized in industrial design and production**.** They work on product design and have an in-house factory with more than 8 facilities and technologies. Prodintec can provide parts to industrial customers in divers industries. Some relevant companies active in the medical sector are Mizar and Aciturri. Also Arcelor metal has a facility located in Asturia.

579 http://www.medgadget.com/2015/09/3d-printing-in-medical-applications-market-future-trends-and-forecast.html
580 Additive manufacturing on its way to industrialisation: a game changer. Cecimo magazine
581 http://www.sirris.be/nl
582 https://www.mech.kuleuven.be/pp/research/rapidprototyping
583 http://mobelife.be/company
584 http://mobelife.be/company

- In the **Netherlands** there are some companies focusing on additive manufacturing e.g. Shapeways, 3D worknet, AdditiveIndustry, Xilloc etc. Not all of them though serve the healthcare market. Xilloc is a growing player in the medical device sector who provide customized implants and surgical planning. TNO also performs research in additive manufacturing but does not solely focus on the healthcare sector. The same counts for some universities like Leiden and Maastricht University.
- In **France**, there is a lot of activity with respect to the use of ceramics for additive manufacturing (which is not a specific focus of this case study). There is the cluster "Pôle Européen de la Céramique" which aims to boost the business ceramics industry. Companies active in additive manufacturing and involved in medical applications are Osseomatrix, 3Dceram, Iceram, Poly-shape, Prodways and Phenix System (part of 3Dsystems). 2PS (Project Plasma Système) is a company which is specialized in coatings from medical applications.
- In **Denmark**, there is Welfare tech which operates a national cluster. It is a hub for innovation and business developments in healthcare, homecare and social services. They are a membership organisation with member from private industry, public organisations and research and education institutions[585]. Additive manufacturing interest in this area mainly concerns prosthetics and orthosis (also exoskeletons). The interest towards customized additive manufactured surgical tools and models seems to be rather limited.
- In **Emilia Romagna (Italy)**, and in Italy in general, additive manufacturing of tools and instruments for surgery appears to be started. There are only limited experiences so far, but some increases in exploitation are possible in the coming months. In this respect it is very important that surgeons are not resistant to the use of new technologies, otherwise the market uptake of customized tools and instruments (produced by additive manufacturing technology) will be difficult.
- Among those leading the advance in the **United Kingdom** is the Centre for Applied Reconstructive Technologies in Surgery (CARTIS), a collaboration between the Surgical and Prosthetic Design team at the National Centre for Product Design and Development Research (PDR) at Cardiff Metropolitan University, and the Abertawe Bro Morgannwg University Health Board's Maxillofacial Unit at Morriston Hospital.

In order to summarize the critical points from the above listing, one could highlight that there is a high level of concentration of AM capabilities in Western-European regions. Key actors can be found in countries with historical links with the healthcare sector. AM capabilities outside healthcare companies are rather located in organisations such as service providers like Materialise (Flanders) and printer manufacturers originating from the United States but also Sweden[586] or Germany (Bavaria for instance[587]).

(ii) Barriers to the uptake and further deployment of AM in the value chain

As indicated, there are multiple applications of 3D-printing possible in the healthcare sector. Some of these applications are already fully deployed such as dental and hearing aids[588]. Other applications like implants are still encountering barriers hampering the further deployment of Additive Manufacturing. According to the interviewees this difference in uptake can be attributed to the following elements:

- 3D-printers can print different geometries at the same time and at large scale;
- Large market for dental/hearing aids (compared to other implants);
- 3D-printing allows customization of the dental/hearing aids;
- 3D-printed dental/hearing aids require less material and tools for applying it to/in the body;

The characteristics of 3D-printing such as customization and requirement of less material and tools for applying it to/in the body are also applicable to hard and inert implants, but these features are more complex than with the dental and hearing aids. In the last year, the uptake of 3D-printed hard and inert implants has grown. Most interviewees agree on the fact that large multinational companies providing implants are most likely already investigating in (if not already using) AM. Key obstacles to an uptake of AM in implants (compared to dental and hearing aids) still remain though. They are depicted below.

Upfront investment cost

Overall, the **large upfront investment** in AM implants by hospitals is a large barrier: design, preparation, printing, post-procesing, packaging, cleaning etc. (especially the design cost is high). An interviewee made the remark that hospitals have different budget divisions: a surgical division which performs the surgery and an implant purchase division. This makes it more difficult to see the total costs of AM implants. The customized 3D-printed implant might indeed be more expensive (upfront investment), but the reduced surgery time and the related benefits for the patient might cover for this additional cost.

585 http://en.welfaretech.dk/

586 See http://www.arcam.com/solutions/orthopedic-implants/

587 See for instance http://www.eos.info/industries_markets/medical/orthopaedic_technology

588 AM is used to manufacture about 90% of the world's plastic shells for custom in-the-ear hearing aids (more than 10 million have been produced). Wohlers 2015.

Value chain specific dynamics:

- **Regulation/certification requirements** are a hampering factor to the deployment of AM in the application are of hard and inert implants. There are a lot of uncertainties with respect to the certification of (customized) implants. Moreover, a long and extensive certification process requires time and money.
  With respect to the **certifications**, clarification was offered by interviewees. The following procedure applies for respectively standard and customized implants:
  - For 3D-printed standard implants a CE-marking is required, as with traditionally manufactured implants.
  - For customized implants, there is no CE-marking required. There are three parties involved for the approval of the use of a 3D-printed implant for surgery:
    - The request for manufacturing an implant via additive manufacturing has to come from a specialist (surgeon).
    - The ethical commission of the hospital has to approve the technique and material used for the surgery.
    - The patient has to agree with the use of 3D-printed implants for surgery.

  The procedure has to also comply with the ISO 13485 standards (or equivalent). The ISO 13485 (2003) specifies "*requirements for a quality management system where an organization needs to demonstrate its ability to provide medical devices and related services that consistently meet customer requirements and regulatory requirements applicable to medical devices and related services*"[589].

  Some interviewees indicated that due to the EU system of national norms and ISO standard, it is more complex for doctors to understand the different applications which requires more research time from their side to select a suitable implant. Also for companies it is more complex to find out to which standards implants have to comply. The uncertainty and lack of knowledge on certification and regulation sometimes prevents AM service companies to enter/expand their activities to the implants market.

  In the US, the FDA is in charge of approval of the 3D-printed medical devices. Up to now, FDA 510 (k) approval was granted to some fairly simple 3D-printed medical devices[590,591]. The uptake of AM in medical product could be hampered by more demanding FDA regulatory requirements e.g. *"the need for large randomized controlled trials, which require time and funding, could present a barrier to the availability of 3D-printed drug dosage forms*[592]*.* The FDA has also initiated a working group to assess technical and regulatory considerations regarding 3D-printing.

- **Intellectual property** issues with respect to the 3D-printing of implants might arise in the future. Scans and design of implants for example can be easily uploaded. The question arises who is the "owner" of a design in case of small adjustment of an existing design. In industry, 3D-printing often occures via contracting. But in healthcare, especially personalized implants, this is more difficult.

Technology and related framework

- The **quality of relevant materials** is very often seen as a main obstacle to the further deployment of AM. In the field of hard and inert implants, health-related constraints apply which require materials to fit certain expectations. For example, a skull implant will require a certain level of porosity and strength in order to fulfil its role. Materials in that respect are to present certain properties to remain constant, which still requires further development from the side of powder developers. R&D with respect to **materials** for healthcare applications is also perceived as being a bigger challenge in healthcare than in other sectors. It is not sufficient to only develop material for AM, it is necessary to develop new materials for specific medical applications. There is still a lot to explore with respect to materials for healthcare AM applications.

- There is a need for a **regulatory framework**, especially with respect to materials and the use of devices. Regulation has not fully catched up with recent developments. Some improvements have occurred but there are still limitations. There is the acknowledgement by interviewees that it is difficult to implement a regulatory framework for AM, as there is a trade-off between achieving good regulation and not limiting innovation.
- It was indicated in the interviews that, compared to Europe, US companies better **manage to implement technology itself in service design**. They manage better to implement the existing processes into a business process. In this respect, it is important to deal with the issue of software planning and to reduce the overall complexity of the planning.

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589 http://www.iso.org/iso/catalogue_detail?csnumber=36786
590 C. Lee Ventola, MS (2014). Medical Applications for 3D-printing: Current and Projected Uses
591 3D-opportunity in medical technology: Additive Manufacturing comes to life. Deloitte University Press, 2014.
592 C. Lee Ventola, MS (2014). Medical Applications for 3D-printing: Current and Projected Uses

Knowledge

- **Multidisciplinary skills are** still very scarce. As indicated, additive manufacturing in healthcare requires insights from engineers, surgeons and radiologists. Combining skills from these three disciplines will be beneficial for the update of advanced manufacturing in implant production.
- There is the need for **skills, talent and training**: e.g. computer-aided design, building operation and maintaining AM machines, raw material development and supply chain and project management.[593]
- Additive manufacturing in healthcare often requires insights from engineers, surgeons and radiologists. There is often still a **lack of multidisciplinarity**. Communication, collaboration and exchange of experiences between the different actors is required, but this is difficult to achieve. Currently there is no wide implementation of specific training yet. This is particularly applies to users who should gain upgraded competences in complex computer modelling[594].
- There is a need for **common standards and further characterization**, especially with respect to materials in healthcare.

Technological performance

- **Technical developments (e.g. structural strength and size)** are still necessary for some applications to fully develop their market potential. Especially with respect to the material, a lot of research still needs to be done. Not all materials used for traditional manufacturing for example can be applied for additive manufacturing. Another challenge is that the application produced via additive manufacturing should be sufficiently strong. [595,596]
- The **design phase** for a customized implants is still relatively long. This puts some limitations on the larger scale production of customized implants. Also the "connection" between CT-data and the intelligent design of applications can still be improved. There is a need for a computational platform which allows communication between manufacturers, radiologists and surgeons.
- The "userfriendliness" of 3D-printers can still be improved. Often there is no automation possible or only semi-automation.

Information and awareness

Information and awareness are very important for the uptake of 3DP in healthcare. First there is the information sharing between the different parties involved in order to be able to develop and produce applications in the healthcare sector. Second the awareness of the end user (surgeons and hospitals) about the existence and the advantages of 3DP applications is crucial for the uptake of the applications.

- **The quality of information** is an issue to the uptake of AM. In healthcare there is often still a lack of knowledge, and even if there is knowledge and information available, the assets which are required to set up communication channels are lacking.
- **Insufficient awareness** about AM and its applications by the end users also hinders AM uptake in the healthcare sector. Surgeons are often not aware of all these applications and if they are there might be still some resistance towards the use of it. From the hospital side, there is often insufficient awareness. Also the upfront cost of the applications is very high and forms a barrier to the uptake. As indicated, in the long run, the total cost might be lower.

Besides current barriers, one should bear in mind that IPR are key to the sector at the level of the designs. IPR are not yet a barrier but could become one when other barriers like the one of certification will be overcome. Among other questions, one will then be about what is indeed about what can effectively be certified and what cannot be.

4.2.4.4 Conclusions: opportunities for public support

The area of inert and hard implant AM knows a certain level of concentration in line with the historical structure of the broader sector. Capabilities are mainly concentrated in Western European regions and the US. New players are however entering the value chain of hard and inert implants, such as new technology service providers. In the future, 3D-printing might also offer many opportunities for the healthcare sector.Some future evolutions identified in the literature[597] and indicated by the interviewees are:

- In the near future (5 years), it is expected that the use of biodegradable material will be more common. Some biodegradable materials in polymers and ceramics already exist. But at the moment, the development of biodegradable material is still mostly in a research phase.

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593 3D opportunity in medical technology: additive manufacturing comes to life. Deloitte University Press, 2014.

594 See http://publishing.rcseng.ac.uk/doi/full/10.1308/147363514X13990346756481

595 C. Lee Ventola, MS (2014). Medical Applications for 3D-printing: Current and Projected Uses

596 3D-opportunity in medical technology: Additive Manufacturing comes to life. Deloitte University Press, 2014.

597 C. Lee Ventola, MS (2014). Medical Applications for 3D-printing: Current and Projected Uses http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4189697/#b1-ptj4910704

- In the near future (5 years), also the 3D-printing of drugs is expected to boom. In August 2015, the first 3D-printed medicine received FDA approval[598]. 3D-printing allows for individualized dosages and unique dosage forms.
- Bioprinting (see Box 42) is often regarded as the most advanced 3D application in the future. Some expect organ printing within 20 years, others expect some more time will need to pass before fully functional organs will be printed.
- In the future, there is also the expectation that implants or organs will be printed in the human body during surgery (i.e. in situ printing). The in situ bioprinting for the reparation of external organs such as skin, has already occurred[599]. Import for the evolution in in situ bioprinting might be the advancements in robotic bioprinters and robot-assisted surgery.

Some of these applications are expected to grow/develop strongly in the coming years. The top three of the most promising markets for additive manufacturing identified in healthcare are[600]:

- Additive Manufactured organs: estimation of 3 billion dollar market in 2025
- Personalized implants: estimation of 30 billion dollar market in 2025
- Printed medicines

Box 42: 3D bioprinting

Tissue and organ bioprinting is still in its infancy (Ventola, 2014). Organ printing is a novel transforming approach in tissue engineering, which has a potential for surpassing traditional solid scaffold-based tissue engineering. The added value of bioprinting over traditional tissue engineering strategies is[601]:

- Highly precise cell placement
- High digital control of speed
- Resolution
- Cell concentration
- Drop volume
- Diameter of printed cells

Although bioprinting is still in its infancy, there have already been some notable milestones (Wohlers, 2015):

- "*TeVido Biodevices, a startup company, plans to 3D-print skin and fat grafts using the recipient's own cells following breast surgery*
- *The PrintAlive Bioprinter from MaRS Innovations, still in development, is said to be capable of printing skin cells, including hair follicles and sweat glands.*
- *Organova has developed living liver tissue for medical and drug research and clinical trials using a 3D-printer that it has been developing and using for years.*
- *Researchers at Princeton University have created a functional ear*."

Up to now though, the organs that have been produced are miniature and relatively simple. There are still remaining some issues to be addressed (Figure 76).

There is the expectation that two-dimensional products (like skin) will be the first applications, followed by tubes (blood vessels etc.), hollow organs and finally solid organs. A time frame for these developments is indicated in Figure 77.

598 https://www.asme.org/engineering-topics/articles/manufacturing-design/3dprinted-drugs-does-future-hold

599 Ozbolat IT, Yu Y. Bioprinting towards organ fabriation: challenges and future trends. IEEE Trans Biomed Eng, 2013;60(3): 691-699.

600 http://www.fabulous.com.co/blog/2015/11/impression-3d-medecine-medical-sante-quel-marche/

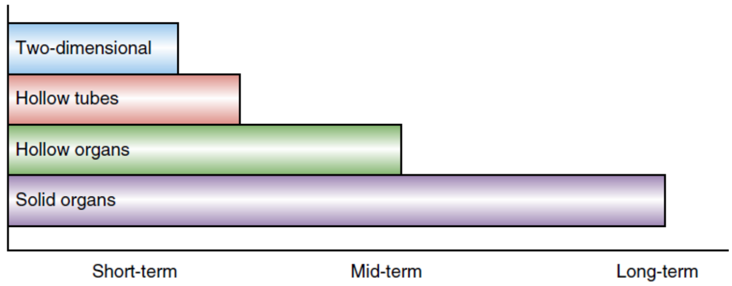
601 Cui X, Boland T., D'Lima DD, Lotz MK. Thermal inkjet printing in tissue engineering and regenerative medicine. Recent Pat Drug Deliv Formul 2012; §(2): 149-155.

Figure 76: Next steps for 3D bioprinting

Area	Focus for future research
Bioprinter technology	Compatible with physiologically relevant materials and cells Increased resolution and speed Scale up for commercial applications Combining bioprinter technologies to overcome technical challenges
Biomaterials	Complex combinations or gradients to achieve desired functional, mechanical and supportive properties Modified or designed to facilitate bioprinter deposition, while also exhibiting desired postprinting properties Use of decellularized tissue-specific ECM scaffolds to study ECM compositions, and/or as printable material
Cell sources	Well-characterized and reproducible source of cells required Combinations of cell phenotypes with specific functions Greater understanding required of the heterogeneous cell types present in the tissues Direct control over cell proliferation and differentiation with small molecules or other factors
Vascularization	Well-developed vascular tree required for large tissues May have to be engineered in the bioprinted construct Capillaries and microvessels required for tissue perfusion Suitable mechanical properties for physiological pressures and for surgical connection
Innervation	Innervation is required for normal tissue function May be inducible after transplantation using pharmacologic or growth factor signaling Simulation before transplantation could be achieved using bioreactors
Maturation	Time required for assembly and maturation Bioreactors may be used to maintain tissues *in vitro* Provide maturation factors as well as physiological stressors Potential for preimplantation testing of constructs

Source: Murphy and Atala (2014)

Figure 77: Timeframe for the development of various types of 3D bioprinted tissues



Source: Murphy and Atala (2014)[602]

1. **Streamlining of the certification process** should be offered by national entities in collaboration with the European Commission services to make sure a certain harmony is found across Member States.
2. **IPR** are key to the sector as they ensure the necessary levels of returns on investment. With AM, the existence of digital designs becomes a potential issue requiring further enforcement of the IPR system as well as subsequent control in line with new AM-related challenges. The European Commission should provide harmony at the EU and Member States level.
3. There also the need for **improving skills**. Skills are particularly needed in areas such as:
   i. (raw) material properties and development (accuracy and fidelity of the material)
   ii. IT (evaluatie/reconfigure CAD/CAM systems, and consider level of integration of IT systems with R&D and manufacturing platforms)[603]
   iii. building operation
   iv. maintaining AM machines
   v. supply chain and project management (allowing to identify opportunities to bring production in-house using additive manufacturing, identify suppliers that are developing AM competence, consider possibility of coproduction with suppliers and customers…)[604].
   vi. Legal skills (awareness of IP issues and regulatory regimes for new production processes and materials).[605]

602 Murphy S.V. and Atala A. (2014). 3D bioprinting of tissues and organs. Nature Biotechnology 32(8), pp773-785.
603 3D opportunity in medical technology: additive manufacturing comes to life. Deloitte University Press
604 3D opportunity in medical technology: additive manufacturing comes to life. Deloitte University Press
605 3D opportunity in medical technology: additive manufacturing comes to life. Deloitte University Press

These skills can be obtained via **education and/or training**. Multidisciplinary training will allow to better understand the different angels that are needed to implement 3D-printing in healthcare applications (surgeons, radiologists and engineers). But more overall there is certainly a need for training to use 3D-printing systems. The current printers are not sufficiently usersfriendly yet. The userinterfaces are often still complex and oriented to/designed by researchers (difficult to use for companies). Training can be organized at the national level, and a coordinated EU approach allows to make sure a certain harmony is found across the Member States.

4. **R&D support** is required to foster new developments in the field. Key technical barriers were already spotted that would deserve attention, such as:
   a. Material properties (polyetheretherketone, metals, alloys and polymers but also ceramics)
   b. Further process characterization with a particular focus on stability and processing affects
   c. Biocompatible and biodegradable materials as well as related effects
   d. Size of AM products
   e. Strength of AM products
   f. Intelligent designs
   g. Diagnostics and censoring and healthcare applications
   h. Bioprinting

   Such R&D requires sustained efforts at the level of fundamental research and could take place in the context of joint Research and Innovation projects that could be supported at all levels of government (regional, national and European). One of the key issues so far is that most developments take place at the level of universities, which highlights the challenge of strengthened Science-Industry Relationships (**SIRE**) on this very specific segment. The multidisciplinary nature of AM in healthcare should be taken into account in the R&D support via multidisciplinary collaboration projects.
5. **Awareness** about AM should be risen at the level of users (surgeons and hospitals). This could be done at all levels of government, with coordination being taken up by European instances.

   In this respect, offering support to initiate studies at hospitals which involve the surgeons and which provides evidence on the benefits of 3D-printed implants (and surgical planning) can help to overcome the entry hurdles of the surgeons and as such improve the uptake of AM in healthcare.
6. In order for the above to take place in a constructive way, further **streamlining of available information** at the EU-level is required in order to overcome the on-going AM "hype" leading to non-realistic expectations. Relevant target groups are doctors, patients, healthinsurance (with respect to reimbursement) and government institutions (institutes for healthinsurance). Initiatives arise from companies themselves, but ethical constraints inhibit them from approaching doctors.

4.2.5 Metal AM for injection Molding

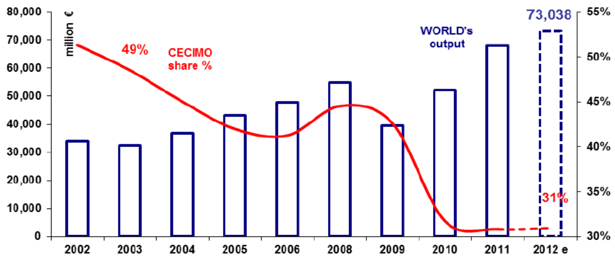
4.2.5.1 Scoping

(i) Context

Machinery and tooling companies produce equipment, tools, machines, and other means for other sectors and to some extent consumer goods such as appliances. It is therefore as diverse as the diversity of sectors served. The machine tool industry produces engines, pumps, turbines, gears, cooling systems, tractors, robots, (automated) tools and machines used in the manufacturing processes of a number of sectors with different technological profiles, from transportation and agriculture to energy and local appliances.

Strongly affected by the 2008 financial crisis, the European machine and tool manufacturers suffers from a weak internal consumption in Europe and a declining position world-wide, while Asia –and China in particular– is on the rise (see Figure 78).

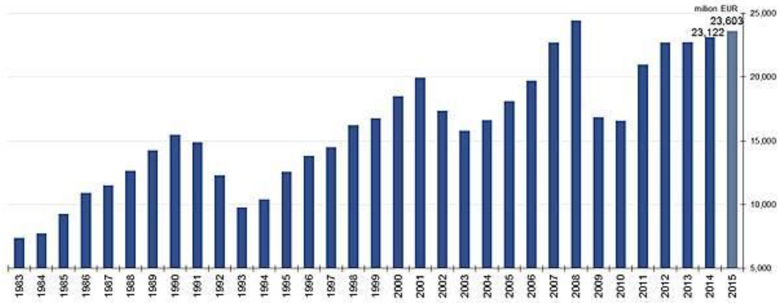
Figure 78: CECIMO's share in world machine tool output in 2012



Source: Geerts, 2013 (Note: CECIMO represents national associations from 15 Member States, equating to 1500 companies, 150 000 employees, €22.6 billion production in 2012 of which 83% exported to reach 44% of exports world-wide).

Figure 79 shows CECIMO's[606] machine tools production from 1983 to 2015 (in million Euros). In 2014, the European machine tool production recorded growth and reached to 23.1 billion euros"[607].

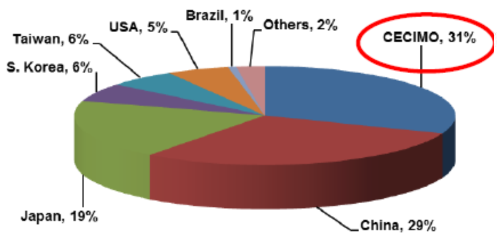
Figure 79: Machine tools production of CECIMO countries from 1983 to 2015 (in million Euros)

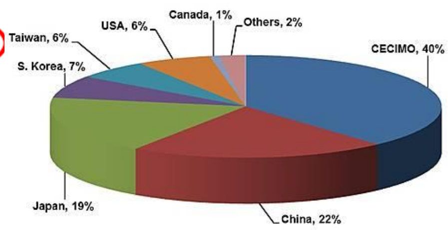


Source*: CECIMO, http://www.cecimo.eu/site/the-industry/data-statistics/latest-trends/*

The volatility in the industry is due to its position on different value chains. Major countries for the machinery and tooling industry are Germany, Italy and Switzerland. Europe occupies an important position in the sector, although China and Japan also occupy a dominant position (with respectively 22% and 19% of the global machine tools production share in 2014 - see Figure 80). 80% of CECIMO's production is exported with 46% of exports outside Europe.

Figure 80: CECIMO countries' world machine tool production shares in 2012 (left) and 2014 (right)





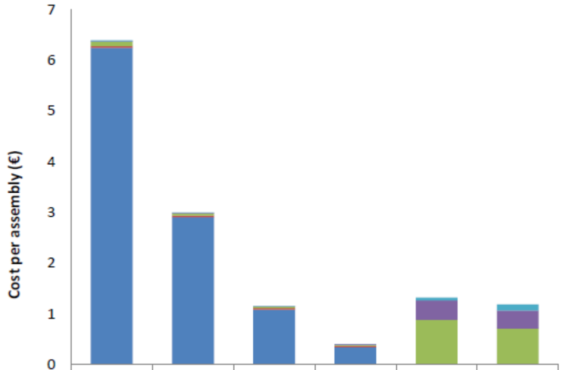
Source: Geerts, 2013 (left figure); and CECIMO, http://www.cecimo.eu/site/the-industry/data-statistics/latest-trends/ (right figure)

Additive Manufacturing is a part of the machinery and tooling industry as printer manufacturers are assigned to this industrial area. Many AM manufacturers are historically involved in machine manufacturing (Renishaw, DMG Mori, etc.). Other machinery and tooling players such as Siemens (automation specialist) also develop AM capabilities to deploy internally but also to serve their clients. AM occupies a paradox position in the machine tool industry as it leads to the reduction of tooling in many industrial processes. As highlighted by Wohlers (2015), "*AM reduces or eliminates tooling*" and leads to the reduction of manufacturing steps. This suggests that AM could potentially substitute itself to certain forms of molding as suggested by Figure 81.

[606] CECIMO represents 15 national associations of machine tool builders, "o*ver 1400 industrial enterprises(...)approximately 80% of which are SMEs. CECIMO covers more than 98% of total machine tool production in Europe and about 39% worldwide. It accounts for over 150,000 employees globally.*" (Source: http://www.cecimo.eu/site/the-industry/data-statistics/latest-trends/)

[607] Source : http://www.cecimo.eu/site/the-industry/data-statistics/latest-trends/

Figure 81: Cost Comparison of Injection Molding and Additive Manufacturing for a Selected Product

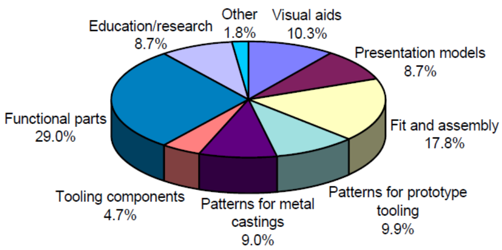


	IM 5000	IM 20000	IM 100000	IM 500000	AM P730	AM P390
Machine operator cost per part	0.018	0.009	0.004	0.001	0.054	0.117
Material cost per part	0.011	0.011	0.011	0.011	0.382	0.360
Machine cost per part	0.083	0.042	0.024	0.014	0.867	0.694
Assembly cost per part	0.035	0.035	0.035	0.035	0.012	0.012
Mold cost per part	6.240	2.900	1.075	0.335		

Source: Thomas and Gilbert, 2014 (reference to Atzeni et al., 2010)

However, AM technologies are used where they are deemed to add value, for instance when coming to prototype patterns or metal casting patterns as suggested by Figure 82. AM leads to patterns for prototype tooling[608] and can be used to directly print tooling components, molds and mold inserts. It is also relevant to the production of patterns for investment casting of metal parts (…) jigs, fixtures, templates, gauges, and drill and cutting guides, urethane casting, and injection molding (Wohlers, 2015).

Figure 82: AM uses by companies

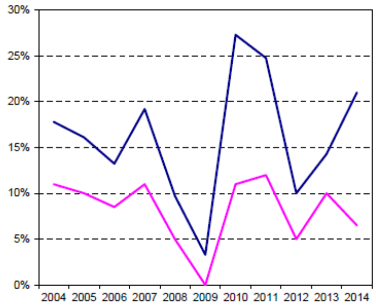


Source: Wohlers, 2015

The present case is focused on the tools used in the manufacturing process and not on machines. Tools usually encompass molds, fixtures, jigs, dies and patterns, but also concerns processes that are described in the next section. Some tools can be used for serial production, while others are only used in limited series. The additive manufacturing of tools correspond to "*secondary services*" and cover "*tooling produced from AM patterns, tooling components produced directly using AM, and molded parts and castings produced from this tooling*" (Wohlers, 2015). Secondary market includes additive manufactured tools and related products produced with these tools. Figure 83 shows the size of the market.

[608] To be understood as tools (molds, dies, etc.) that are used to make prototypes and usually pointed at as "bridge" or "soft" tooling (Wohlers, 2015)

Figure 83: Secondary services market – mean (blue line) and median (magenta line) growth rates; and generated revenues for 2014



	Primary market	Secondary market	Total
Service provider revenue	$1.307 billion	$1.644 billion	$2.951 billion
Non-service provider revenue (includes products, services, etc.)	$2.796 billion		$2.796 billion
Total	$4.103 billion	$1.644 billion	$5.747 billion

Source: Wohlers, 2015[609]

(ii) Application area: Metal AM for injection Molding

Metal AM is increasingly used for the production of tools, although CNC-machined tooling is in general still "preferred" to AM because of costs and efficiency reasons. Some companies such as Volvo in France (Lyon) reduced their tool production time by more than 94%[610]. AM shows a lot of potential for the entire machine tool industry, as demonstrated in the recently established partnership between EOS and the machine tool manufacturer GF Machining Solutions[611]. This case study will focus particularly on the tooling part of the machine tool industry which encompasses a broad range of tools (see Figure 84).

Figure 84: What are tools and dies?

A *tool* is a precision device for cutting or shaping metals and other materials.

A *die* is a form used to shape metal in forging and stamping operations. Dies also include metal *molds* used in making plastics, ceramics, and composite materials.

A *jig* is used to hold metal while it is being drilled, bored or stamped.

"*Tools, dies, and molds are fundamental to durable-goods manufacturing. Tools are used to cut and form metal and other materials. Dies are metal forms used to shape metal in stamping and forging operations. Molds, also of metal, are used to shape plastics, ceramics, and composite materials. Tool and die companies, typically small businesses staffed by skilled craft workers*" (Canis, 2012)

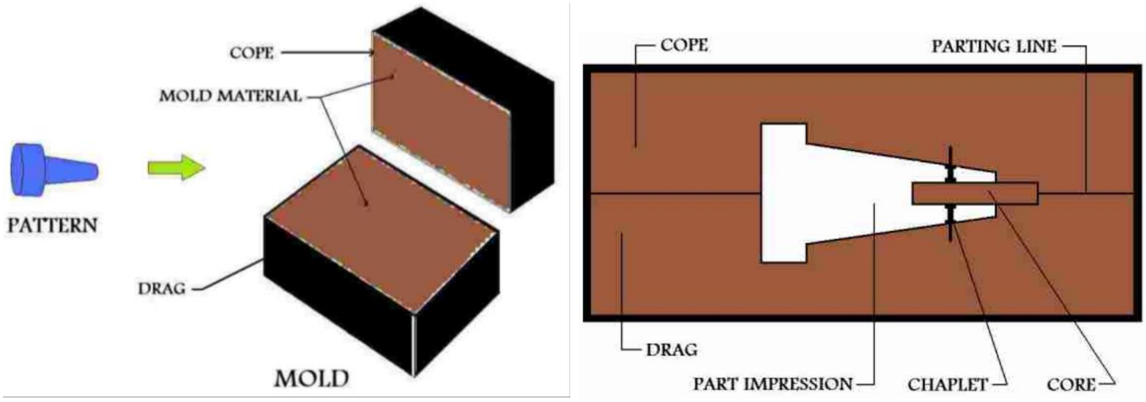
Source: Canis, 2012

The initial area selected for this case study was "Sand & metal moulds and cores for foundries when individual castings are needed. Plastic patterns for sand casting". It was decided to select this area as it operates B-2-B and shows great potential for boosting the competitiveness of traditional sectors. This area is of relevance for all EU countries and reaches out to many SMEs.

In practice, this area covers sand, metal and plastic molds and casts. While casts are used to pour a molten material (liquid), molds are used to shape soft materials. The area also covers patterns as well as cores used in foundry processes. Patterns are replica of the parts to be produced that are used to shape the interior cavity/ies in which the soft or molten material(s) will be poured. Cores are used during these processes to produce internal cavities in the molded part. In summary, while molds and casts are used to pour material that will adopt their geometry, patterns are used to shape up the mold and cores are used as to shape the interior of the internal cavities. Figure 85 illustrates the main difference between a pattern, a mold and a core.

609 The data includes contracts for AM systems, training, seminars, conferences, expositions, advertising, publications, contract research, and consulting services
610 Source: http://www.etmm-online.com/additive_technology/articles/498831/
611 See http://optics.org/news/6/7/11

Figure 85: Pattern, mold and core

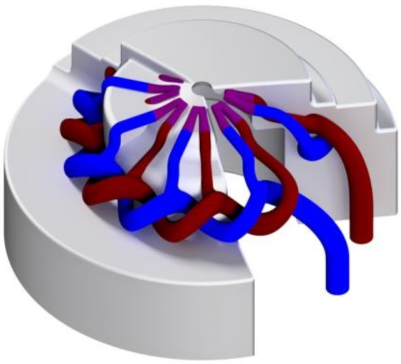


Source: The Library of Manufacturing[612]

Although recent patents were filed for the additive manufacturing of cores[613] used in the casting and molding processes, AM was less used for patterns (as molds can be printed without patterns when using AM).

Thus AM was mainly developed and in some areas used for the manufacturing of molds. Only few cases of cores and patterns could be identified[614]. Additive manufacturing is indeed increasingly being used in the tooling industry where it adds most value e.g. where small (or even unitary) series are to be produced, and where technical challenges require the use of a non-traditional technology. It is therefore of particular interest for the molding industry where inserts (not molds) are printed with AM and then added on the molds. One of the main advantages of AM in the field of molding is related to conformal cooling: with AM, there is no need to dig straight holes in steel molds as it is now possible to optimized cooling channels in molds that are printed with Maraging steel[615] or other metals for instance. The cooling channels can be made quite complex (see Figure 86). Conformal cooling improves the characteristics of the mold and reduces the cycle times.

Figure 86: Conformal cooling: collaboration between CurTec and Melotte



Source: Melotte[616]

In order to narrow down the scope of this case study, it was decided to focus on the application area that best fits the study objectives. While AM shows potential for all tooling processes, injection molding retained the attention of the team as it is a growing market towards which several molding companies turn to. It is also a technique for which AM is reaching a certain level of maturity, but is not yet deployed on the market. Injection molding (in the contrary of sand casting for instance) is used to produce molds that are then used for mass production.

612 See http://thelibraryofmanufacturing.com/metalcasting_basics.html
613 See http://www.patentsencyclopedia.com/app/20150306657 and http://www.google.com/patents/US20130266816
614 See the soluble cores proposed by Stratasys (http://www.stratasys.com/solutions/additive-manufacturing/tooling/soluble-cores) and the offer from the Richland Center Foundry (http://www.rcfoundry.com/iron-casting-expertise/industrial-additive-manufacturing) for instance;
615 Iron alloy with superior strength – see for instance http://www.imoa.info/molybdenum-uses/molybdenum-grade-alloy-steels-irons/maraging-steels.php
616 See http://www.melotte.be/en/3d-metal-printing/reference/conformal-cooling

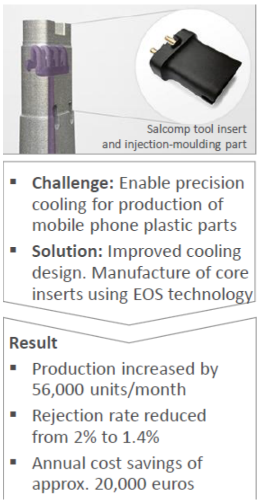
Tools such as molds, casts and dies can be defined by their use (while tools are used to cut and form materials for instance, dies are used in forging as to shape metal, see Figure 84), but are mainly seen from the angle of the production process for which they are mobilized. The dominant techniques are listed below and know different levels of maturity in the use of AM.

- **Die casting** relates to the melting of aluminum parts which are placed for several hours in an oven heated at a high temperature. A key issue is the heat that can soften the mold and eventually break it. AM offers the ability to manipulate the temperature of the mold (pointed to parts not to cool too fast) and enable a better forging of tools.
- **Sand casting** is used for heavy or/and stiff products (such as turbines). This process consists in melting and casting material in a sand-made mold. Sand-based AM technologies[617] exist and are already in use in the industry. In many cases, AM starts to substitute the conventional sand casting techniques as long as the parts are not made in large series.
- **Blow molding** is usually applied to form plastics. Companies in this field are still at early stages of exploration of what value AM can add. Blow molding concerns a narrow number of applications (such as aluminium tooling) although it relates to a large market.
- **Compression molding** concerns pre-heated parts that are placed in a compression mold. It is seen as a large, but shrinking market where fusion AM techniques can be used but where companies tend to move towards injection molding. AM is at an early stage in this area and faces a strong cultural barrier from the companies at stake.

Although the aforementioned casting techniques are concerned with limited series, molding techniques can have a leverage effect in large production series. Most progress have been made in injection molding, defined by Zonder and Sella (2014) as "*the process of injecting plastic material into a mold cavity where it cools and hardens to the configuration of the cavity*".

Injection molding is an area where AM can have a disruptive potential, also with regard to other molding segments which are shrinking as companies turn to injection molding. It is a fast-growing area where AM shows an intermediary level of penetration. It allows to make molds more efficient thanks to conformal cooling and the diminution of cycle times (by 50% in some cases). Injection molding is therefore the area where AM can bring most value (see Figure 87 for an example in which main features of a business case are depicted by EOS).

Figure 87: EOS injection molding case



Source: EOS, 2015

AM in this area leads to more expensive molds, but these molds are far more efficient and therefore lead to savings. It is considered by many as "state of the art", but is not fully deployed on the market – and concerns 5% of the relevant applications (according to one of the interviewees). Moreover, one has to consider the main driver of AM, which is geometrical complexity. AM is often mobilised when complex parts are to be produced, and injection molds have particularly complex shapes that are more likely to benefit from the use of AM.

Additive manufactured molds for injection molding are usually made of metal (aluminum, etc.) and in line with a similar industrial process than traditionally manufactured molds. The user industry shows few signs of willingness to change and adapt to new materials as the processes are well-established among the industry. Therefore, the objective of the AM molds is to demonstrate more added value in a similar framework.

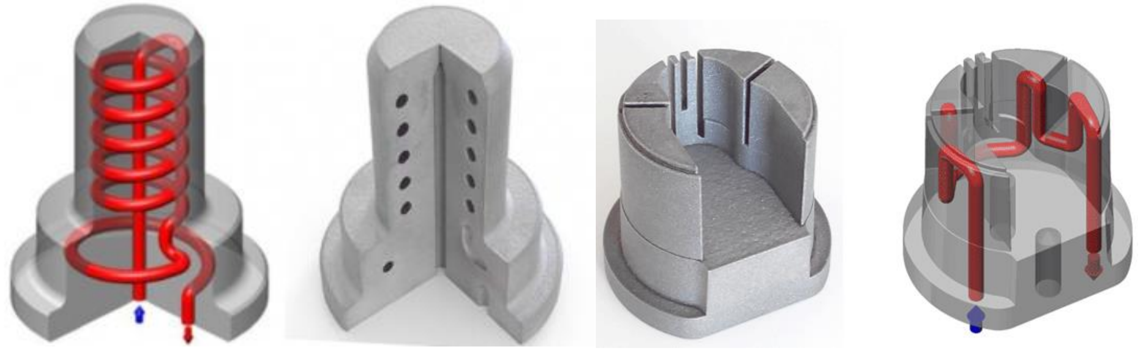
[617] See http://foundrymag.com/moldscores/patternmaker-launch-3d-sand-printing-0

4.2.5.2 Identifying value chain components

(i) Identification of key players and usage of Additive Manufacturing

Through the web-based search and interviews several cases were spotted regarding AM for the machinery and tooling industry. For example, the 2012 Grainger & Worrall case (castings manufacturer) who invested £500 000 in an AM printer "*to help it meet demand for small quantities of development parts for prestigious car brands, including Aston Martin, Bentley, Bugatti, Porsche and McLaren*" and print the "*sand cores to make the mould directly and eliminate the need for the tooling process*"[618]. Other cases showcase DMLS (patented by EOS), such as Spritzguss + Formenbau Bergmann (see Figure 88) who aim to reduce cycle times by 20% and increase the quality of its outputs by 50%, and also aim to produce new tools that have been impossible to produce with conventional technology.

Figure 88: Conformal cooling with EOS' DMLS – Spritzguss + Formenbau Bergmann



Source: Foundrymag[619]

The Wohlers website showcases a number of companies involved in the product development of molds through additive manufacturing, such as the following ones to which specific technologies and products are associated[620]:

- **3D-CAM**: design, SL, LS, rubber tooling, CNC machined tooling, aluminum epoxy tooling, zap tooling, urethane casting, injection molding, QuickCast, and sand casting
- **Alpha Prototypes:** stereolithography, PolyJet, FDM, binder jetting, CNC, and injection molding
- **Applied Rapid Technologies Corp:** 3D design services, stereolithography, vacuum cast urethane parts, and rapid "bridge" tooling for injection molded plastics
- **ARRK:** product Development Rapid prototyping, CAD/CAM, CNC, machining, fabricated prototypes, vacupressure molding, and complete product finishing
- **Bastech:** CAD, engineering, SL, LS, plastic and metal reproductions, prototype tooling, and short-run injection molding
- **CAM-LEM:** uses a special lamination process to manufacture components, prototype molds, and tooling in metal or ceramic directly from a 3D CAD file
- **Proto Labs**: rapid injection molding without the need for steel mold material, EDM, or expensive custom engineering
- **Protogenic**: manufactures prototypes and conceptual models using stereolithography and silicone rubber (RTV) molds for limited pre-production quantities
- **Schmit Prototypes Design**: models, prototyping, and injection molded parts at one location
- **SICAM:** engineering, SL and cast urethane models and prototypes, rapid tooling, injection-molded parts, and offshore manufacturing
- **Stratasys Direct Manufacturing:** FDM, PolyJet, SL, LS, CNC, DMLS, cast urethane parts, investment and sand casting patterns, tooling, and injection molded parts.
- **3Geometry:** laser-based additive manufacturing systems for producing sand molds and cores
- **Axis Prototypes:** LS, SL, urethane prototypes from rubber molds, and on-demand production parts
- **Solize:** a leading CAD, prototyping, and moldmaking service and sales
- **Dinsmore and Associates:** product design, SL, LS, DMLS, FDM, PolyJet, CNC machining, injection-mold tooling, injection molding, and metal castingKAIAO Rapid Manufacturing SL, CNC, prototyping, injection molding, die casting, and part finishing

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[618] Source: http://raconteur.net/business/3d-printers-producing-factory-goods; the article also states that "*parts producer Sigma Components received £140,000 from the UK government through the National Aerospace Technology Exploitation Programme, with which it is using to work with Rolls to 3D-print lightweight pipe end fittings. Also last year, the UK government invested £154 million in four 3D-printing research projects, including one led by Rolls-Royce "to explore new technologies and drive research keeping the UK competitive on the world stage by creating lighter, greener and more fuel efficient aircraft and reduce carbon dioxide emissions by 75% by 2050 compared to levels in 2000"*.

[619] See http://foundrymag.com/moldscores/tool-diemaker-adopting-metal-additive-manufacturing and http://www.metal-am.com/news/002739.html

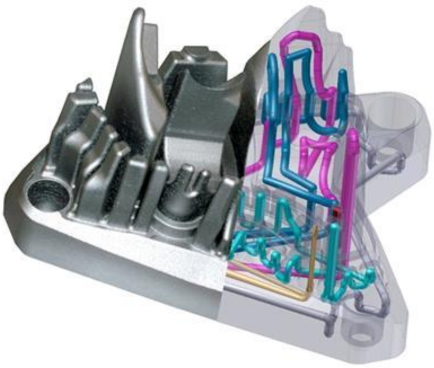
[620] Source : Wohlers, http://wohlersassociates.com/index.html (aggregation of relevant company profiles by IDEA Consult, 2016)

Some of the companies identified by Wohlers that are active in the field were also clearly labelled as European players, such as the following:

- **In Germany, Schneider Prototyping** Stereolithography, laser sintering, CNC machining, molded parts, and metal castings
- **In the UK, Pentagon Plastics Prototyping**, 3D-printing, SL, LS, injection molding, vacuum casting, and mold tools
- **In Germany, MK Technology GmbH** Vacuum casting system for making RTV silicone rubber molds and prototypes
- **In the UK, Omega Plastics**: plastic injection molding, prototype tooling, bridge-to-production molds, and low volume manufacturing
- **In Scotland, CA Models:** SL, LS, CNC, urethane casting, model making, tooling, plastic injection molding, and CMM inspection
- **In Northern Ireland, Laser Prototypes Europe**: SL, LS, reaction injection molding, urethane casting, metal casting, short-run production, CAD, CNC machining, finishing, and painting[621]

Many other cases are available, especially regarding the present case on AM of injection molds. The companies promoting AM for injection molds are the main AM players in the field and belong to the supply side of the value chain: American companies such as 3DS and Stratasys are promoting AM for injection molding as European companies like EOS and Voxeljet do. Also companies like Renishaw (see Figure 89) advertise the use of metal AM for mold tooling, conformal cooling, and injection molding in particular.

Figure 89: Metal AM for conformal tooling – Renishaw



Source: Renishaw

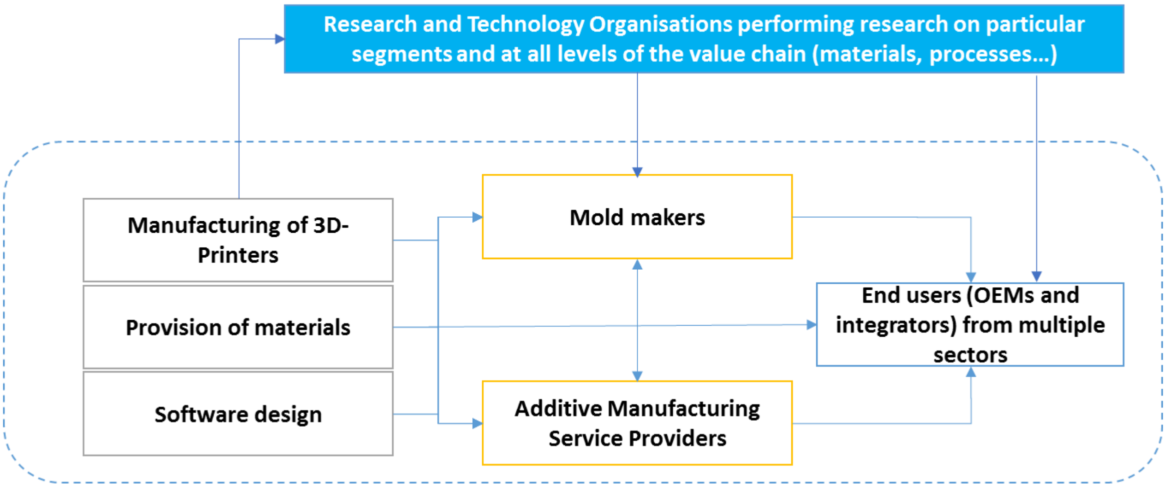
(ii) Composition of the value chain

The value chain of AM for injection molding is marked by a high level of fragmentation at the level of the mold making segment: mold producers are companies that are mainly small and micro companies. From automotive to energy and consumer goods, the mold making industry acts across a broad variety of domains and applications. This implies a variety of molds that can be used for different purposes.

Printer manufacturers supply both mold making and end-user industries. They play a facilitating role in the process of adoption of AM in these two segments of the value chain. RTOs and in particular technical centers are also key enablers in that regard: they provide SMEs with relevant support to demonstrate the value of AM and foster its discovery but also the development of capabilities in companies when relevant.

[621] Source: Wohlers, http://wohlersassociates.com/index.html

Figure 90: Main segments of the injection molds additive manufacturing value chain



The use of AM is determined by several factors, such as the geometry, the quantity of molds to be produced (in the case of AM, usually short series) and end parts (that determine the characteristics required from the molds). The geometry (and therefore precision) of the technology used to produce the mold is of importance. It stands as a first selection filter regarding the technologies that can or cannot be used to print molds. Metal-based AM technologies such as fused metal deposition (FDM[622]) or Selective Laser Melting (SLM) of inox or Maraging are the main technologies used in this value chain; but they require cycle time. They remain the dominant type of technologies used in the mold industry. Other existing technologies would not require such cycle time (like EBM[623] which is used in the aeronautic field) but cannot be used in a molding context due to granularity issues. Besides FDM and SLM, Selective Laser Sintering (SLS) and in particular in reference to the EOS-patented technology (see Figure 91)[624].

Figure 91: Use of DMLS for conformal cooling – consideration from the Wohlers report

Technology	Digital Part Materialization	Direct Metal Laser Sintering	Direct Metal Sintering	EasyCLAD
Conformal cooling	builds conformal cooling channels into tooling without supports (minimal limitations on shape, length, or diameter)	yes (unsintered powder easily flows out of channels)	yes	yes

Source: Wohlers, 2015

Manufacturing of 3D-Printers

The main suppliers are located in Germany, such as EOS, Trumpf, Concept Laser and SLM Solutions. EOS has a particular position in the market as it holds a number of patents in the metal AM area and sold a number of patents to other main industrial players. It has a good visibility on the current market and benefits from the royalties they receive. EOS started with the production of AM 5 years ago and is growing fast (some deliveries include 5 to 10 printers for one client). Voxeljet and ExOne are also part of the leading group of printer manufacturers and located in Germany. However they aim for bigger parts (up to 4m long). Another printer manufacturer, located in Germany, is Envisiontec[625] who showcases luxury and entertainment mold cases.

[622] Which stands for Fused Deposition Modelling
[623] EBM can indeed hardly be used to design conformal cooling channels as it is operated under too high temperatures.
[624] Other techniques can be mobilised to fabricate plastic-based molds in specific cases such as what Stratasys (IL) or OMEGA Plastics (UK) do (see http://www.omegaplastics.com/our-technology/); they however represent a much narrower part of the industry under the scope in Europe.
[625] See http://envisiontec.com/resources/case-studies/

Additional printer manufacturers include Renishaw (UK), KEYEMCE and DMG MORI (JAP). DMG MORI also has a branch in Germany and recently launched (through its Germany branch) the Lasertec 65 Additive Manufacturing, a powder-based AM machine with hybrid functions[626]. In addition, the company 3DS is growing its AM activities in Europe since its acquisition of Phenix Systems in Auvergne (FR) and its partnership with HK 3D in Warwickshire (UK). It is active in the development of printers able to make molds: HK 3D introduced two SLS machines that "*can create injection mould parts without the time or expense of manufacturing tooling*"[627]. D-M-E MoldFusion, a US-based mold specialist that has launched its own powder bed system, also has offices in Europe, and more specifically in Mechelen (BE). Another US-based company, Stratasys promotes the use of its equipment for the AM of plastic-based molds to be used for short series (see Zonder and Sella, 2014). Stratasyss is also active in Europe and owns a service company called Stratasys Direct that provides services to many OEMs but also works with foundries, mold makers and custom molders who supply major OEMs.

Provision of materials

Injection molding implies that materials are injected into a mold to form a shape. Such process implies that the melted or soft materials can be at high temperature and usually require metal-based molds (except for particular cases such as Stratasys and 3DS who propose plastic-based molds for short series production[628]).

The raw material for the production of the molds is predominantly metal. Several types are covered, from Maraging to stainless steel – the main material used remains Maraging. Main providers of metal powders include[629]:

- Eurotungstene (FR)
- Erasteel (DE)
- ATI – Specialty Metal Supplier (US)
- Sandvik (SE)
- LPW (UK)
- Metalysis
- Advanced Powders & Coatings (AP&C) (CA)
- TLS Technik (DE)
- Nanosteel (US)
- Carpenter (US)
- CVMR Corporation (US)
- Plansee (AU)
- GKN (UK)

Most companies are international players, but the list also contains entities such as LSN Diffusion (UK). Also, one should notice that some companies like EOS produce their own powders and intend to make the usage of their printers conditional on the use of their powders.

Software design

Software design can be divided in 1) system software and 2) CAD (design) software[630]. When considering AM CAD software, Solidworks from Dassault is mainly used for the design of products, including the conception of injection molds. Solidworks encompasses functionalities such as the creation and analysis of single and multiple-cavity family molds[631] in a user-friendly fashion. Other tools such as ALTAIR software are used for optimization and re-conception. CAD software include 3DRPD, CA Models, and I2M, but also specialised software such as Moldex3D. The latter is particularly relevant to the present case study as this simulation software "*offers a conformal cooling design tool for plastic injection molding part designers who are using additive manufactured molds for part production*"[632] (see Figure 92). Simulation is key for this value chain and is seen as a segment that could be strengthened in Europe.

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[626] This new machine makes use of Siemens CNC and "*incorporates laser deposition welding into a fully-fledged 5-axis milling machine*" (Source: http://metalworkingnews.info/dmg-mori-presents-an-additive-manufacturing-breakthrough/)

[627] Source: http://www.etmm-online.com/additive_technology/articles/502133/

[628] And for whom main providers in Europe will most likely include companies like Evonik, BASF, or Dupont.

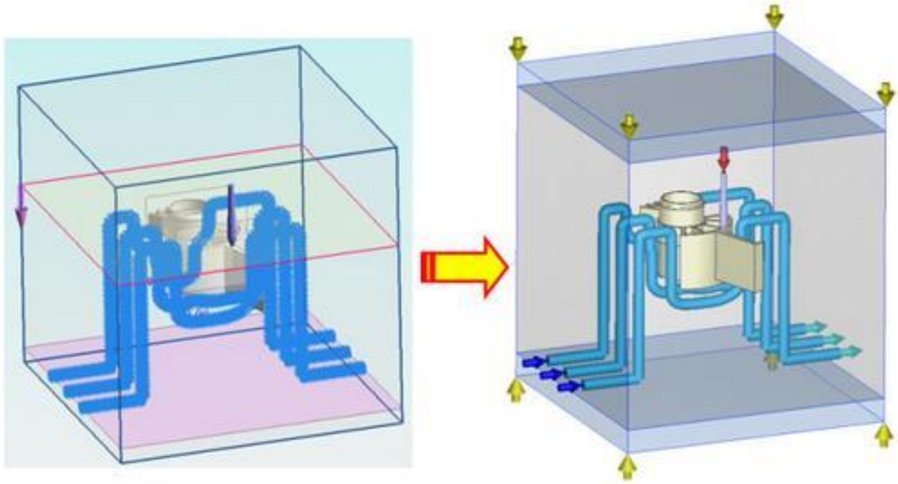
[629] See http://www.sme.org/MEMagazine/Article.aspx?id=2147483814#sthash.hsHFks9G.dpuf

[630] Other softwares such as GOM are used for 3D scanning and measuring and can play an interface role between a possible scanning and the design but do not fall under the scope of AM *in se.*

[631] "*Including sprues, runners and gates*"
(Source : http://www.javelin-tech.com/3d-printer/injection-molding-additive-manufacturing-solution/)

[632] Source : http://www.designnews.com/author.asp?section_id=1365&doc_id=277373&dfpPParams=ind_183,kw_40,aid_277373&dfpLayout=blog

Figure 92: Moldex3D, a software to design cooling channels in molds



Source: Designnews[633]

Connectivity between the devices (computer and printer) is usually ensured as both printers and software function with the drivers required for 3D-printing. Printer manufacturers ensure that their printers apply to the Windows (currently 8.1) standard drivers. The designed software in .stl format are exported to the printer but an additional functionality is required in order to ensure the orientation and position in the chamber, the setting up of laser and support structure parameters, as well as post-processing modalities. This is where the system software comes in as it represents the interface between the users and AM machine. Materialise has a quasi-monopoly on the European software market with its Magic Software, in competition with Stratasys' Solidview, GrabCAD and Netfabb's 3S (DE) software.

Mold Makers

One of the findings from our case study is that small companies turn towards technical centers as they do not have enough capacity (from both a financial and human resource points of view) to test an expensive technology such as AM and thereon develop proper capabilities. It is therefore interesting to note that mold makers can:

- Request services from AM service providers and technical centers; or
- Develop in-house capabilities

Pentagon Plastics in the UK[634] or Schneider International[635] are two companies that develop in-house capabilities: while the former adopted SLA and SLS to develop rapid prototyping services[636], the latter adopted AM for its activities of rapid prototyping and manufacturing[637]. One of the main parameters to differentiate between the two types of company is the fact that mold making businesses developing AM capabilities, are most likely to be tooling companies with a certain critical mass. One of the interviewees pointed to the fact that less than 30 companies in Germany, 2 in Italy and 2 in Portugal would most likely have a sufficient critical mass in the field of injection molding. In France, companies making molds would be micro-companies while larger companies could be found in Germany[638]. One of the recent cases spotted in the media was the one of Spritzguss + Formenbau Bergmann[639] (DE) showing an example of a partnership between Spritzguss + Formenbau Bergmann and EOS. Another success story is DPH International which acquired an EOS M280 machine and created a subsidiary called Hyperion Laser dedicated to the AM of molds. This company invested massively in AM as a result of two projects with the PEP technical center targeting AM integration in molding companies. Only two other mold-making companies are known to own 3D-printers in France according to two of our interviewees.

In general, mold-making companies are at an early stage of adoption, and only lead users manage to test and acquire AM. However, large end-users such as EOMs or integrators (car manufacturers, main airplane manufacturers, etc.) are also using AM and are currently integrating the complete process in-house. The molding activities of these large corporations is not covered by the present segment which relates to companies working in the molding industry and having a large share of their activities dedicated to the making of molds for injection molding.

633 See http://www.designnews.com/author.asp?section_id=1365&doc_id=277373&dfpPParams=ind_183,kw_40,aid_277373&dfpLayout=blog

634 See http://www.pentagonplastics.co.uk/uk-mould-tools/

635 See http://www.schneider-prototyping.co.uk/company.html

636 See http://www.pentagonplastics.co.uk/sla-rapid-prototyping/

637 See http://amsi.org.in/Conference.htm

638 According to one of our interviewees, about 17 employees on average in France, while Germany mid-sized companies would rather have between 200 and 300 employees.

639 Source: http://foundrymag.com/moldscores/tool-diemaker-adopting-metal-additive-manufacturing and http://www.metal-am.com/news/002739.html

AM is used for both prototyping and production of mold inserts. The fast prototyping function leaves the possibility to produce first draft inserts to ensure the mechanical properties of the end product and its resistance to the future conditions of production. These prototypes can also be used for qualification.

A difference should be made between mold makers working on specific products or/and short series (where sometimes only 3 molds are needed), and the molding companies dedicated to large production (such as the manufacturing of bottle caps and bottlenecks, automotive parts, or consumer goods [toothpaste, butter, etc.] that are linked to large packaging production lines).

Additive Manufacturing Service Providers
Some of the main service providers active in Europe provide companies in demand of 3D-printed molds. The American AM and injection molds specialist Protolabs (present in several EU countries) has for instance its EU headquarters in Mosbach (DE). Other companies like Melotte (BE), Brugges Raytech (BE), Layerwise (BE, now 3DS), CA Models SL (Scotland), MK Technology GmbH (DE), and Laser Prototypes Europe SL (Ireland) provide metal AM and other conventional tooling services to companies.

The steps followed by most companies are the following:
1. A service provider would receive a request from a client (and if relevant the piece to be reproduced or adjusted);
2. First feedback including CAD simulations with AM proposals are formulated and sent to the client before any further action;
3. When one or more proposal(s) is/are validated, further study of the mold (re-)design takes place in order to prepare the making;
4. The mold is printed;
5. The mold is post-processed and finalised (whether internally or in partnership with a conventional tooling company);
6. The mold is finally sent back to the client.

Pre-series for large scale productions is the subject of many requests received by service providers. FIT in Nuremberg for example, is mainly active in producing molds and pre-series' parts for the automotive industry. Also Polyshape (now Gorgé) in France produces pre-series of plastic clips via AM-built molds. The pre-series production is an important business area for the service providers producing between 10 000 and 20 000 parts.

End users (OEMs and integrators) from multiple sectors
The interviews led to the conclusion that **thermo-plastics injection molding** is the main sub-sector able to innovate and steer change in the industry. It is also where AM is most developed for injection molding. Injection molding is particularly concerned with large production. It is used in packaging, shoe making, cosmetics, automotive, and other sectors producing a high number of units. Injection molds can be made of titanium, aluminium, Hyperion, Maraging steel, and other types of metals. The molds are usually used to shape plastics, and plastic-based components were pointed by the interviewees as a main development field for AM molds (metal powder injection is also possible but the market is much smaller than plastics in terms of volumes.

Beyond automotive manufacturers such as Renault (FR) or related OEMs like Faurecia (FR) or Bosch (DE), other companies concerned are active in sectors such as packaging, food or leisure:
- Lego which recently entered a partnership with Autodesk[640], produces SLM molds and designs billions of parts every year. Some of these parts cannot be produced without the conformal cooling made possible by AM;
- Unilever (UK and Italy) is using AM to reduce production times by 40% compared to traditional technologies[641];
- Worrel Design and Unilever produce mold inserts for prototype injection-molded parts (Wohlers, 2015);
- Rowenta (DE) is using metal tool inserts made with Concept Laser machines to injection mold plastic parts with conformal cooling (Wohlers, 2015);
- IKEA (NL) is using AM molds for tools used to make plastic bag clips;
- BERKER (DE) makes light switches thanks to molds printed with AM;
- Nestlé and L'Oréal (FR) develop AM, e.g. Nestlé is investigating AM for food and also AM for packaging[642].

[640] See http://www.tctmagazine.com/prsnlz/autodesk-partner-with-lego/
[641] Source: http://www.tctmagazine.com/3D-printing-news/unilever-cuts-production-times-by-40-with-3d-printing/
[642] Source: http://www.confectionerynews.com/Processing-Packaging/Nestle-packaging-project-Reducing-environmental-waste-in-chocolate

Particular applications are mentioned in the automotive sector where thermal exchangers, light components, and new solutions for gearbox are among the molded components where AM could add value in the coming 5 years. However, the most often quoted sub-sector is the packaging sector as quantities produced with molds are the highest in this sector. AM-enabled molds might therefore have a large leverage effect in this sector. Flexibility in design and shorter lead times to obtain the molds (in days or weeks instead of months) are an important aspect for user companies, in combination with the advantages brought by AM in terms of geometrical complexity.

Research and Technology Organisations

Sintef (NO), Fraunhofer[643] (DE)[644], TNO (NL), and Ecole des Mines (FR) are leading organisations in the field and have a long experience of collaborations with companies active in this value chain. The Universities of Munich, Dusseldorf, and Freiburg (DE) and also the University of Zurich (CH) have a track record with the foundry industry and are involved in collaborations with the molding industry. Universities and research centers conduct research on materials and AM processes. Some RTOs are particularly visible in the field of material research (with players such as The von Karman Institute for Fluid Dynamics in Belgium or the Laboratoire IRTES LERMPS in France).

Technical centers are of particular importance in this application area as small companies turn to them to seek solutions and explore new technical opportunities. One should note that most mold makers are micro companies (between 1 and 15 employees) in most EU countries, except for Germany where more mid-sized companies can be found.

In France, the MOULINNOV project steered by Schneider (in partnership with CETIM) aimed at the development of innovative molds for high performance plastic injection. With a €4.6M budget, powder bed fusion[645] was used. Another technical center in France is PEP (European Pole of Plasturgy) that has a long-standing experience in AM and is dealing with the main French industrial players involved in AM research, technology development and innovation. PEP currently has a partnership with EOS. Other technical centers are the Technological Centre for Mouldmaking, Special Tooling and Plastic Industries (CENTIMFE) in Portugal, while VTT is holding a central position in Finland.

Small companies require services from these technical centers in order to:

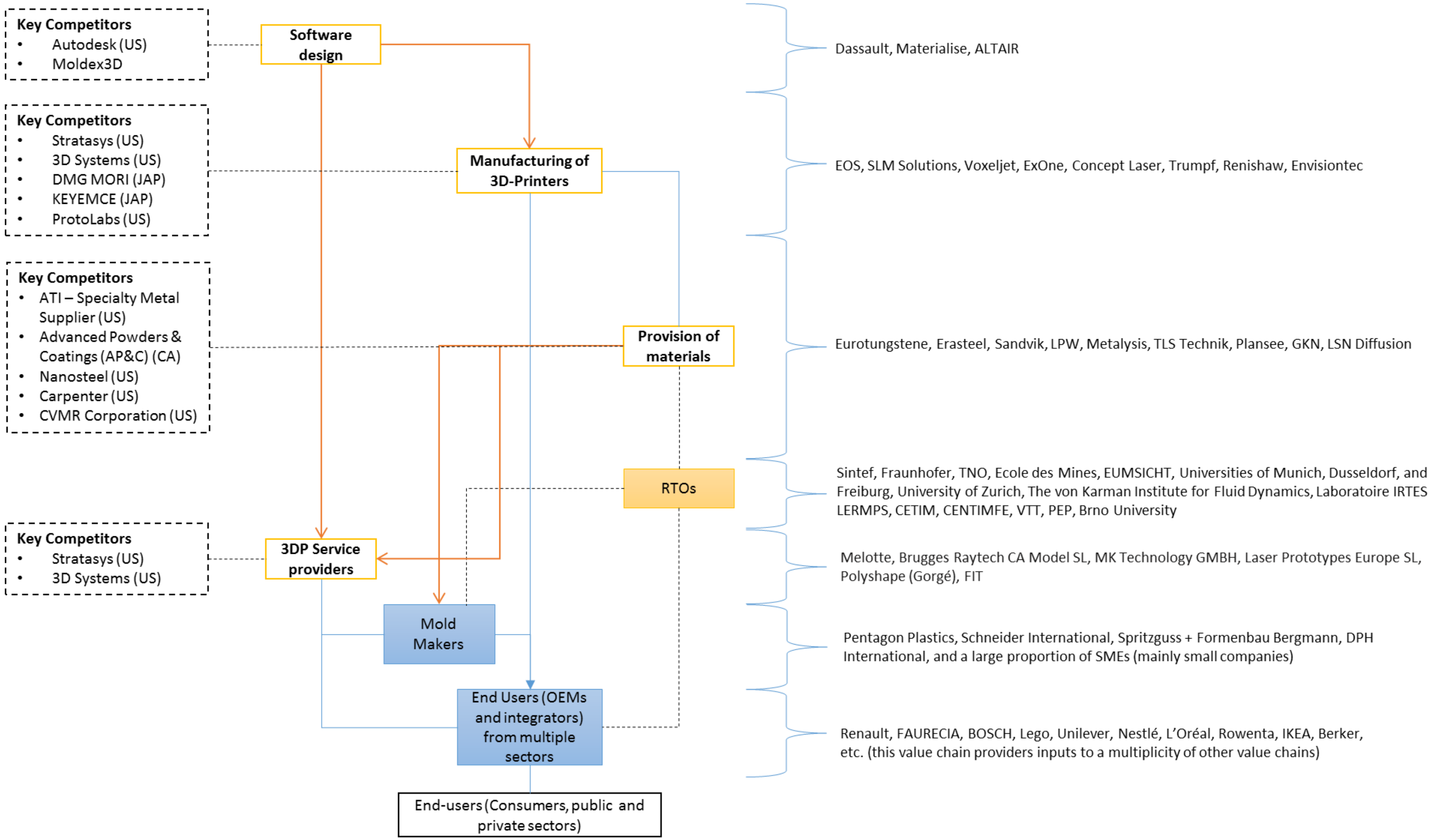
1) Redesign or refine an object (with more than one variant);
2) Produce with a different process;
3) Externalise post-processing (finishing and machining);
4) Test AM (tests can relate to several dimensions such as granularity, geometrical accuracy, defects, porosity, mechanical properties, weight, etc.);

Assess the cost of AM.

Although no clear actor could be identified, some interviewee referred to Croatia, Slovenia (which would be lacking AM equipment) and Czeck Republic (Brno University) where AM is a subject that triggered the interest of the research community willing to develop capabilities

[643] EUMSICHT on materials but also other institutes linked together by a cross-institute AM alliance.
[644] See http://www.umsicht-suro.fraunhofer.de/
[645] Phenix and EOS' machines were used in this context.

Figure 93: Illustration of the value chain



Source: IDEA Consult, 2016

Note: the names of the organisations mentioned are only included for illustration purposes and no colour code was applied – colours codes were only added to make the figure more readable.

(iii) Functioning of the value chain and critical factors

The present value chain of AM for injection molds shows a high level of concentration of AM capabilities in Western European countries. This concentration not only concerns the manufacturing of printers, but also software and materials. Despite of this geographical concentration, the injection molds AM value chain remains fragmented: this is mainly due to the fact that mold making companies provide inputs to almost all other manufacturing value chains, from automotive to packaging. Mold making companies are very often specializing in one or more areas: thus the population of mold making companies is highly heterogeneous as the work performed by a mold maker providing the automotive industry will differ from the one involved in the toy manufacturing industry.

Key players are pushing the mold AM value chain towards major changes. Companies such as OEMs or integrators are progressively developing AM capabilities in-house. Therefore, major companies are now able to print their own molds. Moreover, technical centers tend to foster this process of adoption by all companies. Mold makers (mainly small and micro companies except in the case of German mold makers) usually have limited or no capacity to test and integrate AM as part of their equipment. In addition, AM represents a potential substitute to conventional techniques in the field of injection molding. This substitution will however only be possible when traditional techniques are not cost-efficient anymore compared to what AM can offer, which is not the case yet.

The functioning of the value chain might change in the coming years. For instance a clear concentration is formed in the value chain at the level of 3D-printer manufacturers. These manufacturers are currently disrupting the value chain for instance by providing companies with printers that allow for conformal cooling. An example of externalization is exhibited in EOS' showcase where a mold is being made on a powder bed-fused on behalf of Polymold (DE) and in partnership with BKL Lasertechnik (DE)[646]. The result is a productivity increase of 70% and a reduction of cycle times by 40%. Printer manufacturers are building up AM capabilities in end-user companies and are providing service providers with printers making them able to substitute to mold making companies and produce molds with conformal cooling. As highlighted by an AM online media specialising in engineering, "*A foundation patent for selective laser melting (metal powder bed fusion), held by the Fraunhofer Institute for Laser Technology, will expire in December 2016. This may lead to a new wave of manufacturers entering the metal powder bed market. However, the technical barriers to entry are much higher than for the material extrusion, vat photopolymerization, and even polymer laser sintering*"[647]. The landscape might therefore change further when the patent expires.

The role of technical centers is important as they are crucial for the adoption of AM by SMEs active in making molds[648]. However, the same centers also compete with these SMEs as they are receiving requests from clients such as OEMs and integrators willing to develop in-house capabilities for mass production in an economical way[649]. However, the bargaining power along the value chain is concentrated at the right side of the value chain: users (and not suppliers) are usually steering innovation through their demand. During the interviews, it was found that the further adoption and deployment of AM in this value chain will be driven by the demand side, where requests for more specific and efficient products will be formulated and new specifications will be drafted towards mold suppliers.

From a competition perspective, the price of Chinese molds is far below the European price. The competition in the mold making industry that used to be local is progressively becoming more international. However, the quality of European molds and the shorter delivery times tend to ensure the current market share. Other Asian competitors are to be highlighted, not at the level of the mold makers' segment but rather at the level of printer manufacturers: companies such as DMG MORI in Japan propose new systems combining conventional and additive manufacturing methods (and sometimes hybrid machines)[650], showing a clear technical advantage. With regard to Eastern Europe, several interviewees emphasized the lack of AM capabilities in Eastern European countries.

[646] See https://www.youtube.com/watch?v=zqWOrwBzOjU
[647] Source : http://www.sme.org/MEMagazine/Article.aspx?id=2147483814
[648] In particular as the mold making business is marked by a very high level of risk aversion and conservatism.
[649] See https://www.onlineamd.com/article/airbus-a350-stratasys-additive-manufacturing-050815
[650] See http://en.dmgmori.com/products/lasertec

4.2.5.3 Missing capabilities

(i) Regional dimension and missing capabilities

Western European players and several international players dominate the value chain. This is for instance the case for both materials and software areas which involve a large competition and many international players. The EU capabilities in the software industry are system-wise rather concentrated in Materialise (Flanders) in Belgium and Netfabb (Bavaria) in Germany while competition comes from Stratasys in the US and Israel. In the CAD segment that is used in the molding industry, the following players can be located in Europe: Altair Engineering (Baden-Württemberg) in Germany, CA Models (Central Region) in Scotland; and Moldex3D by CoreTech System Co. Ltd in the United States.

- Main players in materials tend to be situated in either Western Europea or North America: GKN (the section producing powders being located in North Rhine-Westphalia) and Erasteel (North Rhine-Westphalia) in Germany but also Sandvik (Flanders) in Belgium, Höganäs (Skåne) in Sweden and LPW (Cheshire) in the UK. These companies mainly compete with ATI Specialty Alloys and Components and Nanosteel, both from the US. The provision of powders such as titanium powders is seen as a capability that should better be developed as the market is dominated by non-EU Players as well as a few oligopolistic firms.
- Printer manufacturers are important players in the value chain of injection molds for AM. HK 3D (Warwickshire) and Renishaw (Staffordshire) are important British 3D-printer providers, although the dominating players in the market are German companies e.g. SLM-Solutions (Schleswig-Holstein), EOS (Bavaria), Voxeljet (Bavaria), ExOne (Bavaria), ConceptLaser (Bavaria), as well as Protolabs (Baden-Württemberg). 3DS through Phenix Systems (Auvergne) and its UK-based HK 3D branch is a key competitor trying to develop on the European market.
- The mold making industry is characterized by a high level of fragmentation and specialization of most companies in specific application areas, with exception of specific cases such as Spritzguss + Formenbau Bergmann[651] (North Rhine-Westphalia) in Germany. The majority of European companies in this segment are SMEs, including micro-companies (up to 20 employees on average).
- Service providers do not specialise in injection moulding, but rather offer their services as part of a larger set of services. Some of the players with sufficient critical mass even target pre-series production where up to a few thousands parts can be produced on behalf of a large-scale production industry. These companies are concentrated in Western European countries such as Materialise (Flanders), Melotte (Flanders), Brugges Raytech (Flanders) and Layerwise (now 3DS, Flanders) in Belgium, CA Models SL (Scotland) in the UK, FIT (Bavaria), MK Technology GmbH (Rhineland-Palatinate) in Germany, Laser Prototypes Europe SL (Northern Ireland) in the UK, Initial and Shapeways (both Gorgé, Rhône Alpes and Ile-de-France) in France.
- End-user companies are covering a broad range of sectors and all European regions. Several companies that were mentioned are LEGO (Jutland, DK), Berker (North Rhine-Westphalia,DE) and car manufacturers (Bavaria and Baden-Wurttemberg, DE), Renault and Volvo (Rhône-Alpes, FR), etc.
- Technical centers such as SIRRIS (Wallonia) in Belgium, CETIM (Rhône-Alpes) in France and CENTIMFE (Leiria) in Portugal proved to be important to the eco-systems of small companies active in the molding industry. Many actors refer for instance to PEP (Rhône-Alpes) in France which acts as key facilitator of the adoption of AM in the molding industry. Also VTT (Uusimaa) in Finland plays an important role regarding AM adoption by small mold making companies.
- RTOs active in the field are most likely concentrated in the Western and Northern parts of Europe, with the exception of the Brno University (Moravia) which is developing AM. Example are: Sintef (Sør-Trøndelag) in Norway, Fraunhofer (Bavaria, Hesse) in Germany, TNO (South Holland) in the Netherlands, Ecole des Mines (Ile-de-France) in France, the Universities of Munich (Bavaria), Dusseldorf (North Rhine-Westphalia), and Friburg (Baden-Württemberg) in Germany, Zurich University (Zürich) in Switzerland, The von Karman Institute for Fluid Dynamics (Flanders) in Belgium and Laboratoire IRTES LERMPS (Franche-Comté) in France.

Capabilities are therefore unequally distributed across Europe and some of them are even missing: the majority of moldmaking firms are not able to integrate printing capabilities (buy printers) and the powder supply is problematic when coming to materials such as titanium. A clear bottleneck can therefore be observed, which causes can be better understood when looking at the barriers presented in Section 4.2.2.3(ii). One particular difference between Western and Eastern European regions is here that the supply of printers is concentrated in the formers.

[651] Source: http://foundrymag.com/moldscores/tool-diemaker-adopting-metal-additive-manufacturing and http://www.metal-am.com/news/002739.html

(ii) Barriers to the uptake and further deployment of AM in the value chain

As explained in Geerts (2013), one of the particularities of the machinery and tooling sector is that it includes a large share of SMEs. Smaller companies in particular struggle to develop inner capabilities and have a more difficult access to finance but also to foreign markets. In addition, they are limited by their cost structure and face growing competition from Asia (China and Taiwan in particular). Other issues were spotted, such as the shortage of skills or the bad image of the sector that limits its ability to attract young talented workforce. Also, a shift of markets outside Europe and a low demand in traditional markets are seen as challenges to the industry. Each of these factors is to some extent found in the particular field of injection molding, where such challenges can become barriers to the uptake and deployment of AM. More precise limitations were found in the context of the case research on AM for injection molding. These were clustered into 5 main groups of barriers.

Technology access and insufficient (absorptive) capacity

- The sector of injection molding is by far dominated by SMEs, and in particular **small (micro-) companies with little or no AM capacity**. Only remaining medium-sized and large players as well as a very few companies had enough financial, human and technical capabilities that allowed them buy and effectively use one or more printer(s).
- Directly connected to the first barrier (see above point), SMEs have **insufficient access to AM**. This explains the key role RTOs are currently playing in terms of technical assistance, testing and demonstration in the field of AM. However, the outreach of these RTOs appears to be limited to only a share of the population of moldmakers.
- Also **printer manufacturers have limited capacity to address the growing demand** and keep up with the raise of AM in different sectors for which molds are required. The growth of EU printer manufacturing specialists is therefore intense and is in some cases a real challenge for company managers.
- There is also a lack of understanding of the area due to the **lack of streamlined information** and the availability of a high number of technologies. This results in a **demand potential** that is **not fully realised**. This is particularly relevant to customers who are usually not aware of the possibilities offered by AM. Several interviewees pointed to poor quality information as a main challenge in the area. Some also referred to this point and even mentioned that sometimes providers were first to demonstrate the benefits of AM to their client before the latter would accept to shift from subtractive to additive.
- A last point concerns the business culture: the moldmaking industry is less incline to innovate as it very often relies on proven solutions rather than taking the risk of having bad results. Such cultural conservatism is also perceptible in the investments made by the entrepreneurs at stake. Therefore, both **awareness and experience building are missing as well as demonstration activities**. The reluctance to AM adoption does not particularly concern technicians or engineers but is quite relevant to buyers.

Knowledge and technological barriers

- Skills are seen as a main barrier. AM in the field of injection molding involves a broad range of disciplines, among which AM engineering and chemistry are to be strengthened. The development of **AM curricula involves a multi-disciplinary approach that has not yet been concretized**. The lack of appropriate curricula is seen by many as a main threat to be addressed.
- The efficiency of the technology is a key issue that hampers its adoption and diffusion:
    - The first technical barrier is cost-related: **AM remains expensive** and competes with traditional manufacturing techniques that are both proven and cheaper. This is why the use of AM in injection molding so far has been focused on areas where it could add value, such as the optimization of cycle times, the printing of complex shapes and geometries, as well as the integration of parts to avoid assembly.
    - **The lack of performance (size of the printed parts, precision, etc.) appears to remain a challenge**. This challenge applies to many parts in the field of injection molding where AM does not add particular value by allowing complex shapes, etc. Material properties and other technical aspects make AM lag behind traditional technologies when considering non-complex molds. In many instances, AM can hardly compete with other subtractive methods. For example, the range of molds that can be produced is limited by the possibilities offered by today's systems available on the market (which are bounded to the printing of about 4-meter molds). The dimensions are therefore limited and could possibly limit the provision of AM molds to certain sectors in need of larger parts.
    - When considering conformal cooling, **more efficient techniques to clean the cooling channels** after printing are to be developed. This is due to the fact that when printed with powder-based systems, molds are usually to be post-processed. One of the challenges faced at the finishing stage is that powder usually remains in the cooling channel and has to be evacuated.
    - Additive and subtractive methods diverge in many ways, including in the area of design. Even if it is only for optimization purposes, the use of AM implies that the **overall manufacturing process is to be re-thought**. Several interviewees referred to the idea of "*thinking 3D*" and try to dissociate from the usual ways of manufacturing and associated design rules that do not apply to AM.
    - The current state of **qualification and certification** of AM processes and materials is main barrier. This applies also to process simulation that needs to be developed further together with knowledge on how and why AM works the way it does.

- Finally, **know-how** should be developed and awareness should be raised on technical issues. When considering AM for injection molding, one should note that fluidic simulation is of main importance. The design of conformal cooling channels usually implies that some matter is most likely to be stuck in corners where particles might stagnate and block the flows of cooling liquid. Therefore, there is a need to use anti-oxyde fluids, but the know-how about other ways to avoid such issue is still missing.

Powders

- The **availability of powders** is an issue. The supply of raw materials and in particular titanium powders but also aluminium ones have been analysed as a key barrier: it is not that the raw material supply is at risk, but that transformative capabilities are under-developped in Europe. There are several aspects to be highlighted.
  - First, powders such as titanium powder are **expensive**.
  - Second, companies are considering the possibility to develop machines to produce titanium powders but do not take the step as they **do not have convincing intelligence and face uncertainties about future market size for such materials**.
  - The **unfinished process of powder qualification hampers competition** on this market that is subject to some bottlenecks (see point below). Among other topics, powder repeatable quality is for instance to be further understood.
  - Some printer manufacturers linked the use of their printer to the use of their materials. For instance, a printer manufacturer requires from its customers that they use its own powders or else the printers would lose their warrantee. Locked-in systems are considered as a **bottleneck** for many AM users, due to very high costs in comparison with the same materials used with subtractive tecniques.

Competition bottlenecks

There is a fear that has been expressed by several interviewees that ideas could be stolen by real or potential competitors. Several bottlenecks are related to competition and can prove challenging to moldmakers.

- **SOFTWARE**. In the injection molding industry, there is a fear of competition coming from software providers that are also involved in AM service provision. These are seen as (potential) competitors who could steal the ideas generated by moldmakers willing to make use of AM.
- **CLIENTS**. OEMs are developing in-house capabilities, and so are integrators from different value chains (automotive, aeronautics, etc.). The usual clients of moldmakers are in that sense integrating and developing in-house capabilities at the expense of their usual (smaller) providers. The growth of AM is therefore bypassing the segment of moldmakers as complex molds can be designed and printed by the users themselves. As someone has to bear the cost of integrating AM, smaller companies face a bottleneck that is structural and results from their lack of bargaining power in the value chain: as highlighted by an interviewee, they very often not large enough to buy one or more printer, and cannot present an innovative idea without having it possibly stolen by a client (OEM or integrator).
- **FOREIGN MOLDMAKERS**. Moldmakers are facing competition from China which is competitive at the cost level and benefits from a cheaper workforce. However, this threat mainly concerns the production of simple molds and is relevant only to some extent to the more complex shapes AM molds are made with.
- **RTOs.** RTOs are key service providers that allow companies testing and learning about AM. In the specific case of injection molding, they are also raising as competitors to small moldmakers. There is a tension that was referred to by several interviewees concerning the printing of unique molds: although technical centers see such cases as unique, SMEs in the sector perceive them as competition because of the limited number of products usually observed in moldmaking.
- **Plastics**. Although it was not emphasized as a main competition factor, the raise of plastic-based AM applications is a potential threat to metal-based ones. This applies to the molding industry to the extent it is concerned with molds that are not subject to too high temperatures.
- **AM**. To some extent, AM service providers and printer manufacturers are competing with traditional moldmakers. This is not yet consensual but was raised by several interviewees during the case study research. The use of AM is indeed progressively replacing prototyping and production in some specific industry cases.

4.2.5.4 Conclusion: opportunities for public support

Metal AM for injection molding is a field characterized by a high growth potential and an important level of fragmentation due to the high proportion of small companies. AM in this area has a disruptive potential and can impact a broad range of manufacturing sectors that make use of molds. It is already subject to changes in the value chain: OEMs and integrators are indeed growing AM capabilities for tooling while their traditional mold providers struggle to overcome the costs of AM adoption. Only a few lead-users among smaller moldmakers could stand out and acquire one or more printers. New application areas are taking shape as illustrated below:

- One of the growing markets of AM in the field of injection molding is the one of **pre-series production**. Closely related to this market, an emerging trend could be identified which is the **emergence of AM to make prototype molds**. Prototyping is used as to obtain a first version of the mold cheap and fast. This first version of the mold is being produced with the same technology and in the same conditions and showing the same resistance to the process that the end mold itself, although the prototype version is a simplified version of the end mold. The prototype is used to operate a number of checks and mechanical tests, and can be used to produce a few pieces (4 to 5 pieces) in that respect. The potential of such development lies in possible qualification of the prototypes, and a reduction of development processes of particular products. In terms of applications, specific parts in the automotive sector were said to cover interesting potential as they could benefit from 3D-printed molds: thermal exchangers, light components and new solutions for gearboxes. These are only examples as AM molds could add value to many other applications such as bottle caps, etc.
- Other emerging areas are developing, such as the **full development of digital solutions**. This implies that the solutions are fully designed and developed in a digital format, without automatically using scanning but counting on software advances to develop and engineer the molds.
- Another trend rather links to the technique used in the production process. Like in many other industries, AM is part of a broader manufacturing toolbox. One of the emerging area is therefore the one of **hybrid systems combining subtractive and additive methods**, although a few such systems are already available on the market.
- **New materials** are also being increasingly used or targeted by AM moldmakers: the use of AM for thermoplastic injection molding is an example. Another exemple is the printing of bi-material molds (in copper and steel for instance).

When analysing barriers to the adoption and deployment of AM as well as the value chain and emerging areas, key **policy implications** could be identified. Three of them would require priority attention:

1. To foster the adoption of AM in the area of injection molding, one has to:
    a) **Compensate for the high cost of printers** (by either reducing this cost or contribute to the increase of SMEs' capability to buy one). Here possibilities can be explored at all government levels. One example is the one of innovation vouchers that could facilitate the access of SMEs to relevant RTOs;
    b) **Inform and change the culture of small companies** that could benefit from AM but only focus on subtractive techniques. This can be operated in different ways depending on the government level (awareness raising at the EU level, training at regional and national levels for instance). Several interviewees explained that there is a need for **demonstration** support. However, demonstration is to be clearly linked with support to the adoption and development of AM capabilities in small businesses.

    Supporting the acquisition of AM printers by SMEs therefore implies public (co-)investment in SME's capabilities as well as actions focused on human resources.

2. **Powders supply and availability** are critical. Although the field is currently dominated by the use of maraging steel, other powders are of key importance could prove to be critical to specific demanding applications for which AM molds are being (or will be) printed. This is the case of **titanium** and to some extent aluminum. The market is currently dominated by foreign players but no critical risk is associated to the supply of these materials at a raw material stage. A bottleneck is however observed at the level of the transformation of these raw materials into relevant AM materials (mainly powders in the present cas). There is a need to **support and foster the setting up of EU metal powder transformative capabilities and in that respect:**
    a) **Develop and facilitate the access to market intelligence** (at the EU level for instance) in order to foster uncertainty reduction and increase the possibility for private actors to make the right investments**;**
    b) **Facilitate business development** (while the EU sets up the right conditions, regions and Member States can co-invest through different instruments and support capability development)**;**
    c) **Accelerate the qualification/standardization of powder materials** (at the Commission level)**. Inter-operability** of powders across available systems is a key issue in that respect.
    d) Support the **setting up and development of relevant material transformation capabilities** and related businesses with a particular focus on promising materials such as titanium (which implies that the European Commission first coordinates the possibility of connecting required capabilities before support can be provided by any level of government);
    e) Strengthen and further **develop urban mining** initiatives.
    f) Ensure faster qualification of powders by **bringing relevant communities around a same table**. CEOs and key managerial representatives of key organisations could be part of such consultative process and collaborate in that respect.
3. There is clearly potential for **cross-regional support to demonstration activities** in the field of metal AM for injection molding. This support could first take the shape of connected capabilities across regions, where the European Commission could play an orchestration role by setting up, supporting or even coordinating specific networks. This holds two different dimensions:

a) The potential for **joint actions and collaboration** in general most likely lies in the role of RTOs willing to act as test facilities and guidance for SMEs willing to explore and eventually adopt AM. Here, the model of one-stop shop developed in the context of projects such as I4MS, ActPHAST but also in the Vanguard Initiative would appear relevant. This is also relevant in Eastern European regions where current AM capabilities are mainly concentrated in a few leading RTOs (for instance in Czech Republic, Poland or Slovenia).
b) The supply of AM systems and related knowledge is mainly concentrated in Western European regions. Except for Poland, Eastern European countries have extremely little capabilities in AM. Therefore, cross-regional collaboration could foster the **connection between existing supply and demand**, and could lead to technology absorption by Eastern European regions.

Complementary policy implications should be put forward as they were also pointed as crucial by the interviewees. These are the following:

4. **Support is to be brought to emerging areas** such as multi-material or digital design and software development. This support is most likely to be brought by regions supporting R&D, Member States, and the European Union through Horizon 2020 and subsequent Framework Programme(s).

5. The future of AM molds (at least partly) lies in its combination with traditional subtractive techniques that are particularly key to the finishing and post-processing of the printed molds. Therefore, **hybrid manufacturing methods should be further developed and promoted** for instance via R&D and demonstration support at all levels of government.

6. Skills are a fundamental issue for companies willing to adopt and develop AM capabilities. Therefore, several interviewees pointed at the **urgency to develop appropriate curricula**, not only in engineering and chemistry disciplines, but cross-disciplinary. This implies that R&D experts from different disciplines are to be brought together in order to discuss the integration of existing knowledge repositories and how new ones could be developed. In this context, a coordination and matching role could be taken by the European Commission in view of facilitating such a process to spill-over to all Member States.

7. A lot of fear was expressed during the interviews by companies afraid that their ideas would be stolen (by service providers, RTOs, OEMs, etc.). Therefore, **the enforcement of IPR regimes** at the EU and national levels is pointed as a track to follow. This particularly concerns the protection of design patents and copyrights over original parts that might be reproduced.

8. There is a need to **raise awareness among potential customers** who could use AM on molds with high leverage power (for instance in high-rate production industries such as packaging and automotive). In addition, awareness should be raised acrros EU companies regarding IPR management[652]. Such awareness could be raised at the EU level through web-based channels and events.

[652] One of the interviewees pointed at the fact that there would be a "*lack of financial power of small companies to start a law suit with bigger companies. Also, there is sometimes a customer-supplier relationship that prevents people naturally from suing their customers*". The same interviewee recommended the launching of a "*best-practice book that provides models for small companies in order to avoid IP problems right from the beginning*".

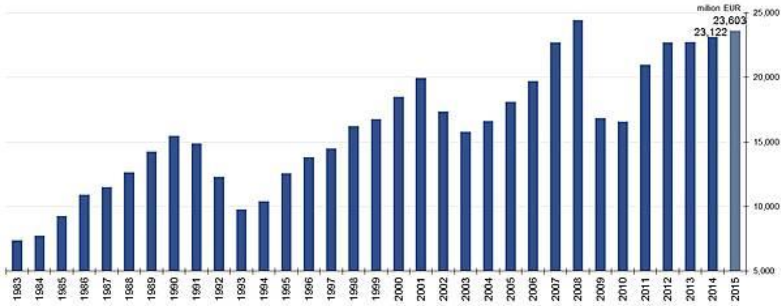
4.2.6 Spare parts for machine

4.2.6.1 Scoping

(i) Context

Machinery and tooling is a sub-sector of the mechanical engineering sector that is mainly made of small and medium-sized companies in Europe. It is historically closely linked to other sectors, such as metal-working (steel and iron) industries but also electrical engineering[653]. The machine tool industry Production in the sector reached its highest level in 2008 as it was strongly affected by the financial crisis (see Figure 94).

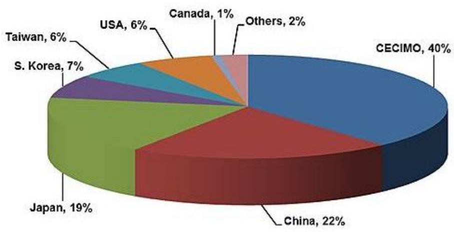
Figure 94: CECIMO's machine tools production



Source: *http://www.cecimo.eu/site/the-industry/data-statistics/latest-trends/*

Despite of the competition rising from Asia – and from China in particular – CECIMO's countries[654] reached a €23.1 billion production output in 2014, with Germany, Italy and Switzerland in leading positions. Figure 95 provides an overview of the world-wide leaders in the production of machine tools. Main Asian competitors include China (with 22% of production share) and Japan (19%) followed by South Korea (7%) and Taiwan (6%). United States and Canada only share a small share of the world-wide production (respectively 6% and 1%).

Figure 95: Global machine tools production share (2014)



Source: *http://www.cecimo.eu/site/the-industry/data-statistics/latest-trends/* in reference to national associations and Gartner Group

Vieweg et Al. (2012) noticed that the "*majority of output* [from the machine tool sector] *consists of capital goods dedicated for investment in a broad range of industries*". Machine manufacturers are indeed very often specializing in one or more sectors. Among the main sectors in demand of machines is the automotive sector. The machine tool industry supplying the automotive EOMs and manufacturers is characterized by a level of concentration that is higher than in other branches of the machine tool industry. This is mainly due to the fact that the industry deals with large contracts, tough price competition, production volumes and requirements associated to the machines in that particular field (Vieweg et Al., 2012).

AM is another sub-sector of the machine tool industry that has been growing at a fast speed over the past 10 years. About 30% of the AM market covers machines (including system upgrades and aftermarket services), while about 50% concerns services and about 20% materials (see Figure 96). Figure 96 depicts the growing position of AM among the sectors falling under the umbrella of the machine tool industry. AM grew by 20% between 2004 and 2014 and grew by 30% between 2010 and 2014. Although it remains a small industry compared to the overall €60B machine tool market, it is expected that the AM market (comprising systems, services and materials) grows exponentially in the coming ten years[655].

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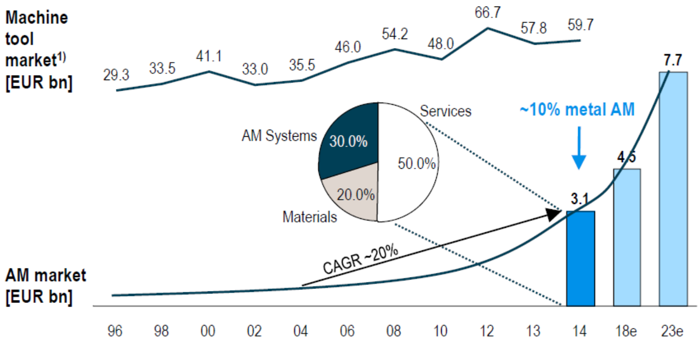
[653] Source : Vieweg et Al., 2012

[654] CECIMO represents national federations from 15 EU countries, covers more than 99% of the total machine tool production in Europe and 30% worldwide and accounts for about 1500 companies among which more than 80% are SMEs fir almst 150 000 employees (See http://www.cecimo.eu/site/about-us/).

[655] Source: Roland Berger, 2015

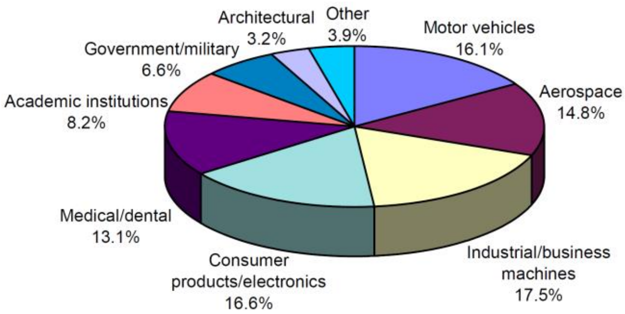
Figure 96: Growth of the AM industry (+20% between 2004 and 2014)



Source: Roland Berger, 2015

The particularity of the machine tool industry is that it provides a broad range of sectors with inputs, and in particular manufacturing sectors. This also applies to the AM industry. According to Wohlers (2015), 17.5% of AM systems is sold to players involved in the sector of industrial and business machines (see Figure 97). Figure 97 provides a general overview of the main sectors to which AM systems (3D-printing machines) were provided. The area of industrial and business machines comes first with 17.5% of the systems, followed by consumer products and electronics (16.6%) and motor vehicles (16.1%), aerospace (14.8%) and medical and dental applications (13.1%). These 5 main sectors are seen as the pioneering sectors for AM technologies as they were among the first adopters of AM systems.

Figure 97: Systems provided by the main AM manufacturers per sector – results from the Wohlers survey



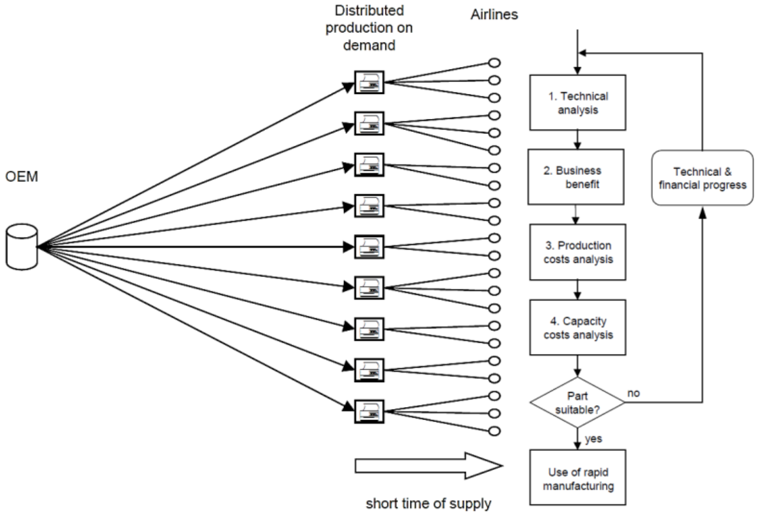
Source: Wohlers, 2015

The possible benefits AM can bring to short series production and prototyping are particularly known, for example product optimisation, parts integration and other technical advantages compared to conventional techniques. Less is known on maintenance, repair and overhaul (MRO) aspects, additive techniques can also be used to repair and replace components[656]. AM is in general expected to make existing supply chains more efficient by reducing inventories and spare parts, allowing for localized and on-demand production (GAO, 2015). This is of crucial importance for instance to certain sectors where parts are stocked for decades before being thrown away (in case of non-use).

The use of AM to print spare parts triggered a lot of expectations, especially among the authors and technicians who imagined the generalization of AM (which could virtually be used to print any spare part): for example, Walter et Al. (2004) anticipated on the impact of AM over the aircraft manufacturing value chain (see Figure 98). Figure 98 compares the production of spare parts as it currently functions in the industry to what it could look like in case AM use would be generalized to the production of spare parts.

[656] See http://www.sdi.com/resources/videos/additive-manufacturing-how-3d-printing-will-revolutionize-mro

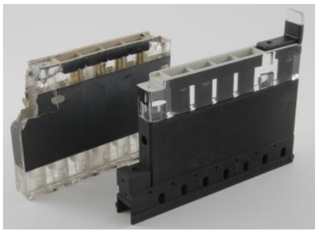
Figure 98: Producing spare parts on demand locally (left figure) and Procedure to assess feasibility of introducing Rapid Manufacturing (right figure)



Source: Walter et Al. (2004)

Still regarding the general use of spare parts in the aviation sector, Matthew Bromberg (president of aftermarket, Pratt & Whitney) predicted "*that maintenance, repair and overhaul (MRO) shops in the future will "print" the parts they need with additive manufacturing technologies, speeding up repair tasks and reducing stored inventory*"[657]. The printing of spare parts is already dispersing to different areas such as automotive. Materialise manufactured for instance spare parts for a 55-year old Mercedes – more specifically bottom sections of backlights (see Figure 99).

Figure 99: AM spare parts for the Mercedes 300 SL



Source: Materialise[658]

The use of AM for spare parts could be identified in large sectors such as automotive and aeronautics (see Box 43). However, in most cases the focus is on the production of parts for end products and not spare parts for machines. The project showcased in Box 43 was referred to by several interviewees and has a high level of visibility in Europe. The consortium in charge gathered key players from the automotive and aerospace sector as well as OEMs and AM suppliers (including printer manufacturers and material providers).

Box 43: DirectSpare

The 2009-2012 FP7-funded project DirectSpart brought together industrial leaders to investigate the use of AM for spare parts production. The project investigated barriers to AM which were referred to as 1) Materials, 2) Business models, and 3) Processes and quality insurance. The main outcomes of the project were scenarios, business models and a roadmap to guide future developments in the field of AM for spare parts.

Source: *www.direct-spare.eu*

But aerospace and automotive are not the only sector where AM for spare parts is being investigated. Other companies are a few steps ahead and not only conduct pilot production projects on the topic but also apply the

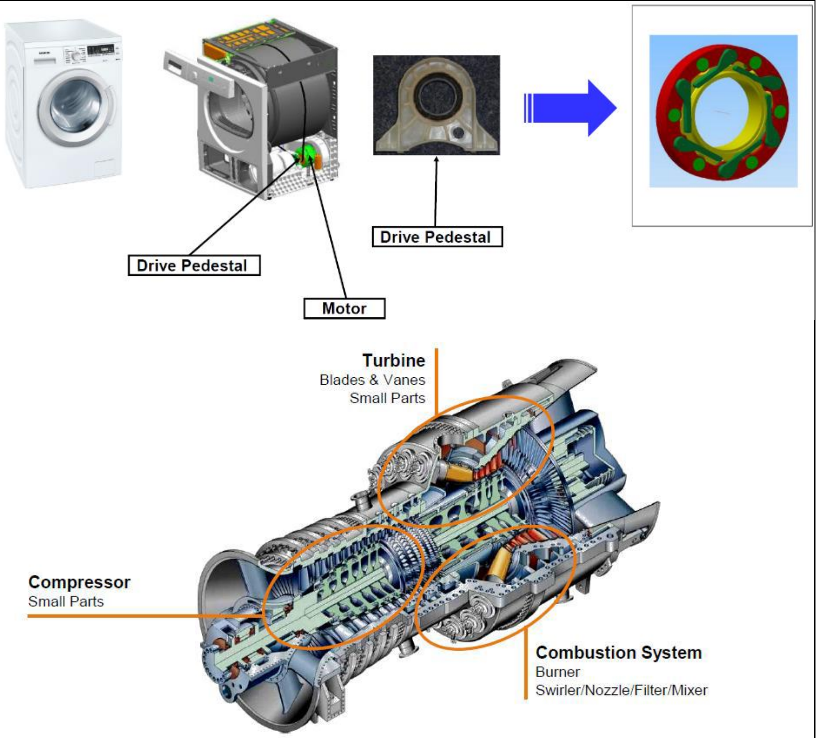
[657] Source : http://aviationweek.com/mro/pratt-whitney-predicts-additive-manufacturing-every-shop
[658] See http://www.materialise.com/cases/bringing-back-the-spirit-of-a-classic-sports-car

principle to their own organisation. The AM of spare parts requires major changes in the organisation of a companies' facilities such as the need for a distributed network available over the globe. Although no particular case for spare parts in machinery could be identified, several cases focusing on end products are spotted e.g. of the case of Siemens (Box 44).

Box 44: Siemens – spare parts for domestic appliance and energy sectors

In the repairing of gas turbine applications, Siemens has achieved a cost reduction of its maintenance activities of about 30% associated to a diminution of invested time by 90%. Siemens is also using EOS machines to repair gas turbine burners with nickel-based super alloys where the repair time has been reduced by 10 times. The maintenance costs are drastically reduced, and the case is seen as a strong basis for "Spare parts on demand"[659]. Also GE is following similar tracks for its own gas turbines[660].

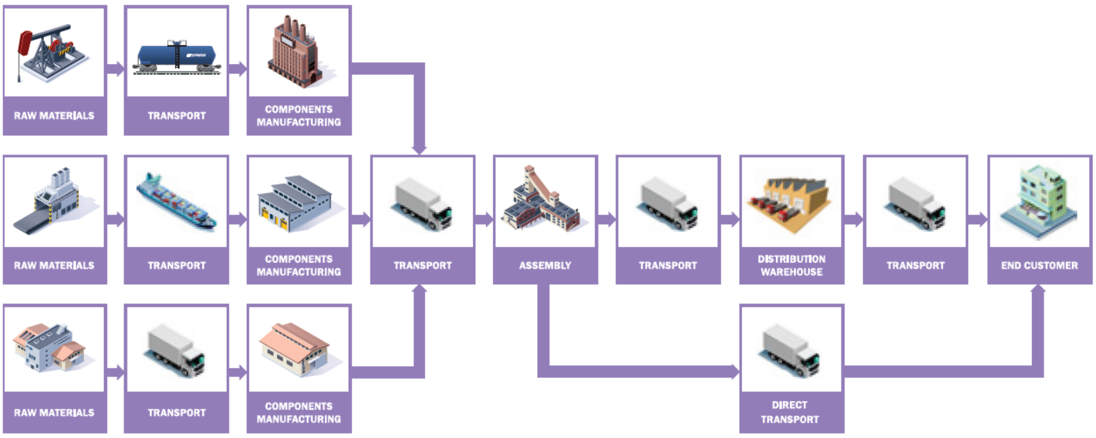
Source: De Wever, 2015



(ii) Application area: spare parts for machine

AM of spare parts for machines is also promising. In the US for example, inventories are currently estimated to stand at $1.7 trillion or 10% of the American GDP (Source: Graham Tromans in CECIMO, 2015). By reducing and reshaping stocks and inventories, AM could prove to be highly disruptive, also in the way logistics would be mobilised. The current manufacturing landscape is shaped by activities and functions that (when not integrated in a same site) involve shipping of products, materials, etc. from a place to another (see Figure 100).

Figure 100: Simplified traditional supply chain network structure

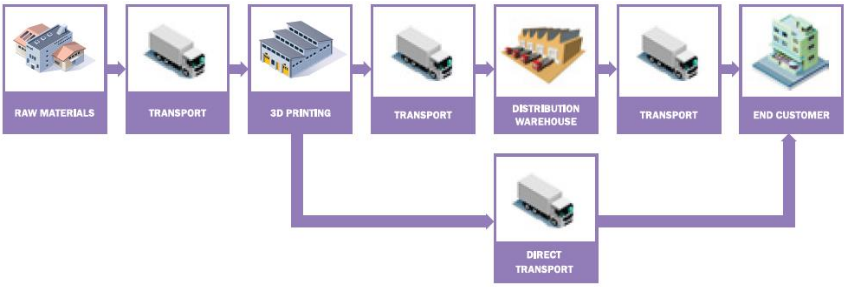


Source: Janssen et Al., 2014

[659] Source : https://www.youtube.com/watch?v=zG_yZmwPhIU
[660] Source : http://3dprintingindustry.com/2015/08/26/siemens-gas-turbines-to-get-a-boost-via-uk-metal-3d-printing-company/

With AM, supply chains could be altered and the number of segments could be reduced. Logistics could be mobilized for the supply of powders while decentralised AM production facilities would be dedicated to MRO and spare parts production activities (or to production, including of spare parts). Figure 101 illustrates such reduction of material and product shipping.

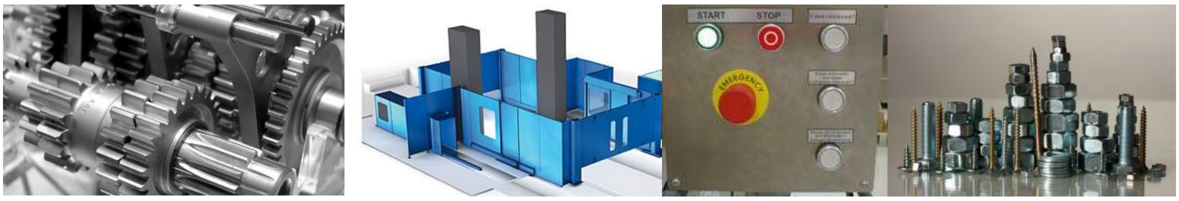
Figure 101: Supply chain network structure with 3-D printing competence



Source: Janssen et Al., 2014

The present case study deals with the use of AM to print spare parts, with a particular focus on spare parts for industrial machines. The area selected during the first phase of this project is entitled "Spare parts for machines (e.g. gears, housings, buttons, and fasteners)". It has a strong potential for cross-value chain impacts, and addresses the B-2-B market. The connections between this area and a large set of manufacturing sectors such as automotive, construction, energy, etc. make it an enabling area of activity. In the context of this case study an emphasis was placed on gears, housings, buttons and fasteners (see Figure 102).

Figure 102: Machine gears, housings, buttons and fasteners



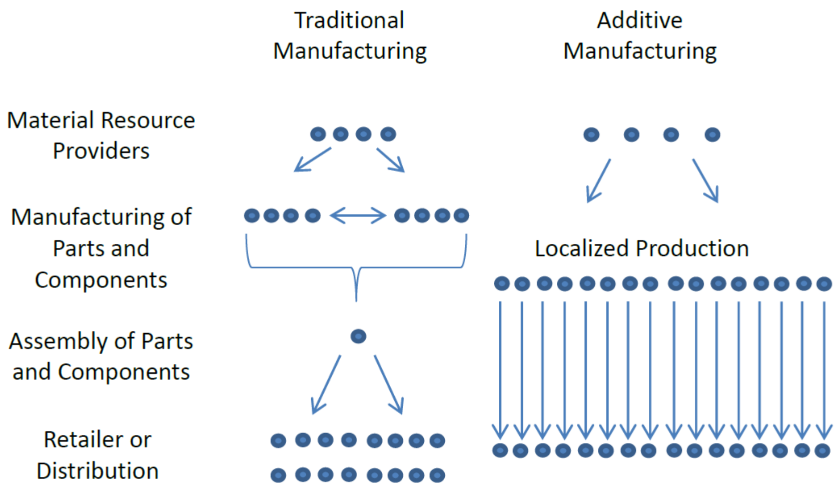
Source (from left to right): Industrial Gears Manufacturer[661], KabelSchlepp[662], Machinery Safety 101[663] and Melfast[664]

It has however not been possible to narrow down the scope of the area due to a lack of information concerning applications that have really be tested in practice. No case of AM of the elements under the scope of this case could be found by the team that showed a level of satisfactory level of maturation.

The area was therefore broadened again to spare parts for machines. This encompassed a broad range of possible parts. From the literature review and interviews, only a few experiences could however be reported that are mainly to be associated with a stage of experimentation, rather than effective use aiming to turn the current supply chain(s) into more efficient chains as suggested by Figure 103 in which the AM of spare parts would lead to localized production of the parts to be replaced.

[661] See http://www.industrialgears.in/blog/applications-of-different-industrial-gears/
[662] See http://kabelschlepp.de/en/products/machine-housings/index.html
[663] See http://machinerysafety101.com/2009/03/06/emergency-stop-whats-so-confusing-about-that/
[664] See http://www.melfast.com/blog/2014/11/how-to-determine-what-fastener-types-to-use-for-industrial-machine-construction/

Figure 103: Turning to efficient and distributed manufacturing



Source: Douglas and Gilbert, 2014

There is no main reference framework dedicated to the categorization of spare parts for machines. Machines however encompass a number of components (most of them recurrent) for which spare parts can be needed: pinions and gears, pipes, helical shafts, sprockets, but also clutches, drag brakes, slip couplings, electric motors and controls, machine frames, welded joints, fasteners, etc.

A broad range of parts could therefore virtually fall under the scope of this case study, whether plastic or metallic parts, or whether mechanical elements[665], structural elements[666] or elements used to control the machine process[667]. Among these elements, both "*repairables*" (repairable parts, usually modular) and "*consumables*" (parts that are not repairable when they fail) could benefit from AM as AM could be mobilized either to replace failing parts or produce replenishment spares.

Although the specific elements under the scope (gears, housings, buttons, and fasteners) were not subject to AM, other machine parts were tested by different organisations as to prove the potential of AM. These cases however remain at a low maturity level as they mainly consist in researching and testing. For example, Figure 104 showcases the output of a cooperation between VTT (FI), EOS (DE), Sandvik Mining and Construction Ltd (FI).

Figure 104: Distributor valve 3D-printed in the context of a VTT AM Spare Part project

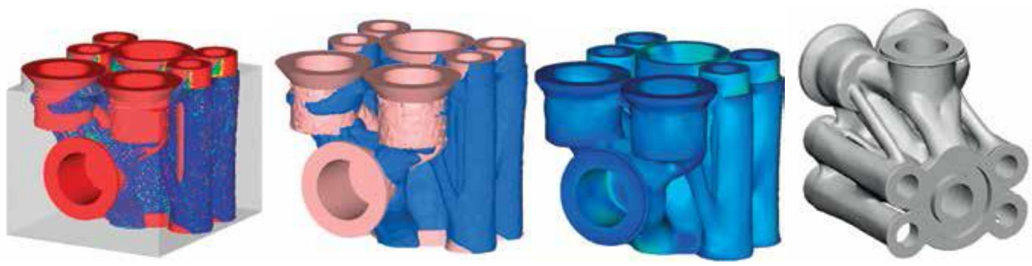
On the left machined distributor, in the middle printed distributor after hardening and on the right printed distributor after hardening and grinding.

Source: Laitinen et Al.

Companies usually investigate the use of AM for its efficiency and supply chain compression potential. Figure 105 present another example of a collaboration between VTT and SLM-Solutions concerning a hydraulic valve case. This case illustrates the topology optimization process that led to the design of a CAD file "*ready for printing*".

[665] Without which the machine cannot function such as gear trains or clutches.
[666] Axles and fasteners for instance.
[667] Buttons, sensors, etc.

Figure 105: Hydraulic valve block for High-Performance

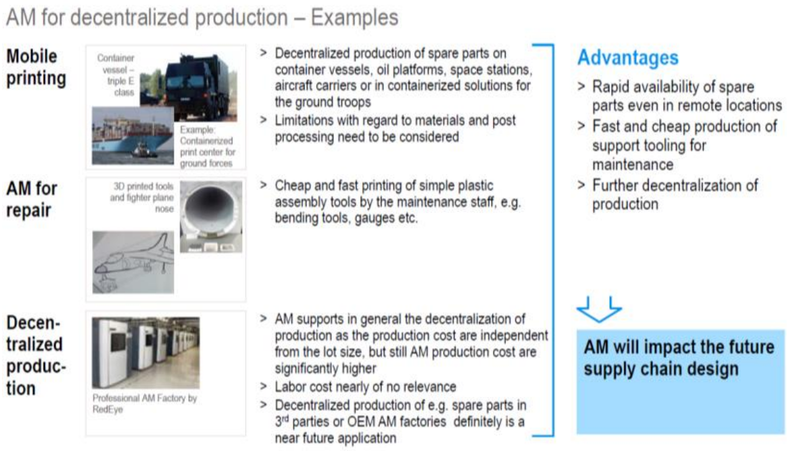


From left to right: *1) Topology optimization result (element density color contour plot), 2) Interpretation and remesh of topology optimization result, 3) Analysis of smoothed optimization design and 4) Final smooth CAD file, ready for printing.*

Source: SLM Solutions

Not only the private sector but also public entities explore the efficiency gains that can be derived from AM and its potential for decentralized production. The Army and Navy in the US are putting particular efforts in the exploration of the topic of AM for spare parts and inventory reduction and already experimented with AM of small parts such as "*valve stem covers for vehicles and onboard logistics parts for ships that are difficult to locate such as drain and valve covers*" (GAO, 2015). Such disruption pathway is also explored as a relevant track for the EU (see Figure 106).

Figure 106: Decentralized production will impact service business



Source: Roland Berger, 2015

The NASA calculated that OEM spare parts printing could lead to a reduction of warehouse footprints by 50% (see Figure 107). Still in the aerospace sector, the F-18 spare parts supply chain was studied by Khajavi et Al. (2014). They found that centralized production with AM was still to be preferred given the current state of advancement of the technology while "*distributed spare parts production becomes practical as AM machines become less capital intensive, more autonomous and offer shorter production cycles*"[668]. The US army however operates part warehouses with 3D-Printers being for instance located in containers in Afghanistan in order to have production closer to fields of operation.

[668] Source : Thomas and Gilbert, 2014

Figure 107: Extract from the 2015 NASA Technology Roadmaps

CAPABILITY	
Needed Capability: On-demand manufacturing of spare parts to support Earth-based ground operations.	
Capability Description: Provide 3D printing or additive manufacturing as a process for making a 3D solid object of virtually any shape from a digital model. Technology creates an adaptive capability for supporting manufacture on-demand while reducing launch costs associated with the logistics footprint.	
Capability State of the Art: Stockpiling OEM spare parts in large logistics facility.	**Capability Performance Goal:** Provide 3D printing or additive manufacturing as a process for making a three-dimensional solid object of virtually any shape from a digital model.
Parameter, Value: Logistics costs within program lifecycle cost resulting from logistics warehouse footprint.	**Parameter, Value:** Percent reduction in logistics warehouse footprint: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

Source: NASA, 2015

4.2.6.2 Identifying value chain components

(i) Identification of key players and usage of Additive Manufacturing

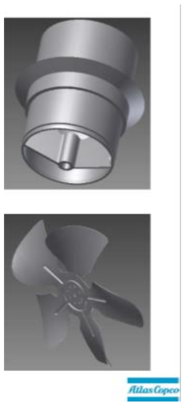
When considering the broader area of spare parts for machines, it is possible to identify either **isolated cases** of AM of spare parts for machines or signals from companies that would be using AM for that purpose but keep their practices under the seal of **secrecy**. Therefore, the only information publicly available concerns isolated examples of AM of spare parts for machines, or examples of companies that are known to use AM but in a confidential way due to the differentiation potential of the technology. The identification of key players was therefore mainly driven by the existence of evidence on specific test cases or AM research projects. Only a few players seem to have experimented with the use of AM for spare or replenishment parts for machines. Interviewees agreed that all major industrial manufacturers developing AM capabilities are also investing its use for on-demand generation of spare parts. Most of them are actively analyzing the potential benefits of AM for spare parts (see Box 45).

Box 45: AtlasCopCo

AtlasCopCo assessed the integration of AM for spare parts using a cost-based calculation methodology. The assessment tool allows selecting commodities that could benefit from the use of AM spare parts. All parts requiring approvals, complex parts[669], and parts with critical material properties were excluded from the scope. In the case of AtlasCopCo, the selected commodities are rather focused on castings forgings and plastics. The plastic parts were assessed using a tool developed by the VIL[670]. SLS-printed PP/PE protection caps for instance are subject to a cost reduction of 35% (small quantities and no mold investment) while PP fan cowl assembly could benefit from the integration of three items into one. The assessment of the metal parts did not lead to positive conclusions as their printing cost was too high to justify the use of AM. A case opportunity cost was however identified regarding the AM of brass couplings for which suppliers have stopped production and for which replacement imply the replacement of the pipes on the related compressor (and therefore a high service cost).

Plastic parts

Metal Parts



Brass couplings

Source: Corne, 2015

AM is currently in the scope of all major industrial companies in the automotive, aerospace, energy, but also medical sector. These industries rely on heavy machinery: this is also the case of the packaging sector (see Paul Howells from Unilever in the AM Strategy Positioning Paper 2015 UK). In the **packaging** sector, companies are very eager to investigate AM for spare parts (see Box 46). In this sector, the machines last between 30 to 50 years and have parts that could benefit from AM such as air compressors. On such a long timeline, it even happens that the machine manufacturers do not produce the relevant spare parts anymore or that the supplier is out of business. Potential companies include the food leader Nestlé (FR) and Tetrapack (SE) where stocks and inventories reach a critical stage, and the manufacturer of air-jet and rapier weaving looms (as well as related spare parts) Picanol (BE). Also Krones AG (DE) is involved in a project to identify relevant spare parts to be produced with AM. As molds are losing their properties with time, a company like Wärtsilä (SE) is interested in onsite production and reduction of stocks that allows the company to avoidshipping large parts to power plants all over the world. The company collaborates with Aalto University in order to explore solutions of which AM could be part of. Other companies such as the COESIA Group (IT), from Emilia Romagna as well as Sacmi (IT).

Box 46: IMA.it

IMA.it is currently collaborating with BC, a local service provider from Imola in the area of Bologna. The IMA group created in 1961 generated over €1 billion turnover in 2015 and provides packaging machines and services to industries such as pharmaceutical, liquid filling in sterile conditions and tea bags packaging. Alike its main competitors, IMA has a world-wide outreach and employs people in Italy, Spain, France, Germany but also India and China. Its corporate R&I unit is now investigating AM and facing the difficulties related to such process of investigation and testing. The value of AM for each line of production will highly depend on the number of machines sold as well as on the value of AM for long-term replacement of parts. AM however opens new possibilities (such as the possibility not to provide spare parts to their clients but geometries and designs). Risks are however remaining and the adoption of AM is still hampered by its technical limitations but also IPR issues (in case a design is sold, the possibility remains that someone else copies it). The use of AM would be focused on non-precision constrained parts. The possibility exists that localized hub exist in every country where both machining, AM and finishing would be integrated in the near future and will therefore lead to reduced value chain activities.

[669] such as coolers for instance that require re-engineering costs.
[670] See http://vil.be/

Among the **isolated cases** are collaborations between industry and research organization, mainly in view of testing particular solutions. Also large companies develop knowledge, test and further develop their use of AM. This is the case of Siemens that produces spare parts both for their clients and for internal uses. Siemens is in the process of actively integrating AM in their organization, and is supporting some of its clients in the integration of this technology. The company is known to use AM in the energy sector and in particular for the enhancement of gas turbines and for spare parts where time reduction on maintenance can be achieved. Siemens is exploring different business cases which they want to keep confidential. In some cases, the use of AM for spare parts would lead to a maintenance time reduction of 90%: this is the case of the burner tips for use as replacement parts in gas turbines that are being manufactured by AM. Other components under scope, such as "*sparovation parts*" are part of the services provided by Siemens[671] as an AM spare part provision service. Figure 108 shows the example of a modified armrest in the Combino Cab (German rail vehicle). The use of AM for the production of spare armrests led to an improvement in the technical characteristics of the part that prolonged its life cycle time.

Figure 108: Example of Additive Manufacturing within Siemens

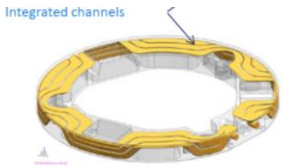
Source: Huber, 2015

Some of the companies buying 3D-printers keep their use of AM for spare parts **secret** and only provide limited information and their practices and ambitions. This is the case of ASML (see Box 47) which claims to have 30 parts in AM production. Companies are able to develop internal capabilities by entering in close collaborations with printer manufacturers. Among the leading companies are Trumpf (DE), Renishaw (UK), Concept laser (DE), SLM Solutions (DE), EOS (DE), Phenix (now 3DS, FR), Fives (FR), ARCAM (SE), Realizer (holder of the SLM technology license together with FhG, DE) Stratasys (which is currently the only manufacturer of a multi-material and multi-color printer, US) but also producers of hybrid systems such as DMG MORI (JAP) and Mazak (JAP).

[671] See http://www.mobility.siemens.com/mobility/global/en/services/spare-part-services/pages/spare-part-services.aspx

Box 47: ASML

The machining solutions provider ASML is using AM for targeted spare parts, although the technology remains rather new to the organisation. Today, ASML claims to have over 30 parts in AM production (Loncke, 2015). The company demonstrated a 90% reduction of disturbances in PEEK and titanium components thanks to AM (see below, left figure) and thermal control improvements on conditioning rings by 6 times together with better dynamics improved by 15% (see below, right figure).



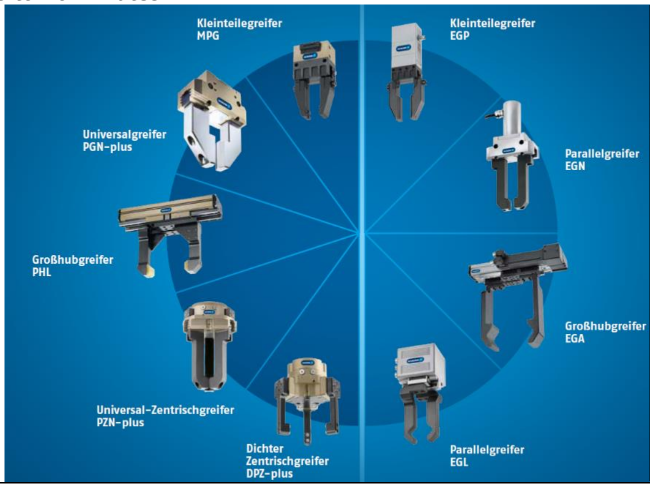
Other improvements were brough to monolythic components that were optimised thanks to AM. The parts were made more robust and lighter by changing the design of the mills, bringing additional improvement in terms of the flows and dynamics (see below, left figure). Process reduction was also organised for the AM of another component – the process of machining, joining, treating, checking, packaging and transporting of a part with cooling water and air channels was drastically reduced (see below, right figure).

Source: Loncke, 2015

Several service providers such as Melotte (BE), Layerwise (BE), and Materialise (BE) collaborate with the industry on the spare parts topic. Specific cases are however showcased on different websites and platforms managed by companies such as shapeways, Sculpteo or Thingiverse propose spares printing. EOS (DE), Layerwise (BE, now 3DS), Materialise (BE) and Stratasys (IL/US) were identified as AM suppliers helping companies printing spare parts. However, some companies are reluctant to work with service providers active in the same field as they fear that some of their development ideas might end up being reproduced by other competitors. An example of a **collaboration** between a company (Schunk, DE) and a service provider is the following: Schunk (Box 48) in Germany collaborates with Materialise on a platform to produce and deliver AM gripper fingers. These grippers require particular geometries and most are no longer available in stocks.

Box 48: Schunk

The German Schunk Greifer (Schunk Greifer, 2015) offers a service that consists of 3D-Printing grippers fingers. Both pneumatic and electric grippers are under the scope of the company's offer which claims to have the world's first fully automated web-based 3D design tool for the additive manufacturing of gripper fingers, called SCHUNK eGRIP. The order is said to take 15 minutes for a 1-week delivery time and a production time decreasing from 2 to 8 hours to 10 minutes.



Source: Schunk, 2015[672]

672 See also http://www.schunk.com/schunk/schunk_websites/news/subject_of_the_month.html?article_id=25113&country=INT&lngCode=EN&lngCode2=EN

Mass production sectors were pointed at by the interviewees as the ones that could benefit the most from AM spare parts for machines. Packaging was a first example. Another one is the **automotive** industry. In the car industry, replacement parts are usually though of for old, expensive models or F1 cars. Brands such as Koenigsegg and other high-end car manufacturers fall under the scope of the expected benefits from AM. Gregory Flinn reported for optics.org that AM is a "*popular tool in motor sport and in automotive development, as highlighted by EOS and (...) Maximilian Meixlsperger from BMW's Rapid Technologies Center. The BMW Center has 14 assorted additive manufacturing systems from the likes of SLM Solutions, Concept Laser and Trumpf, and handles some 90,000 components each year (80 per cent outsourced) as part of BMW's 'fit for test' and 'fit for build' development programs. He said that the use of additive manufacturing at BMW grew by 140 per cent from to 2011 to 2012".* There is however an untapped potential in the sector: expensive machines (such as to press metal sheets) are expected to function for decades and show a great leverage potential. In case of malfunctioning, a machine impacts large series of parts and products. AM is therefore relevant to the needs of the sector. Some companies such as Volvo Truck already develop AM for tooling and are likely to work on spare parts as well. Also engineering companies working with automotive players are involved: the Blok Group (NL) for example provides services to the automotive sector (tool provision and machine operations), and started to develop AM capabilities in the context of a partnership with Concept Laser and Landré[673] (NL). Another company, Eriks (NL), is also working with AM and is active on a similar segment. Other players in the automotive sector are also researching AM, such as Carglass in France.

The use of heavy machines also concerns the **equipment manufacturing** industry. Sandvick Coromant (SE) and SECO Tools (SE) are both developing AM for internal purpose. Other players from the separator industry such as Alpha Laval (SE) are also proactively looking into the possibilities offered by AM. Also AtlasCopCo is working on prototyping and spare parts production via AM such as air compressors and compellers. Mapal is currently working with Concept Laser. Only Schunk (Box 48) seems to show a entry-to-market level of maturity.

In the field of machinery in general, the importance of testing the technology is seen as problematic for smaller companies. This is crucial for sectors such as the machinery and tooling sector – SMEs account for 80% of CECIMO's members. These companies do not have enough capacity to buy a machine and therefore properly test AM. However, interviewees report a high level of questioning from the industry as a lot of potential is seen for AM spare parts in all sectors. In addition, AM still has to develop as to overcome remaining technological barriers: one of them is the limitations encountered by AM in terms of precision – which mainly concerns surface finishing. The surface finishing and the necessity to present similar mechanical characteristics compared to the initial part are important constraints for AM spare parts as most 3D-printers have not yet reached the same level of precision and affordable prices. Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Fused Deposition Modelling (FDM) technologies are the preferred technologies because of their advances in surface granularity compared to less precise printing technologies (such as EBM). Surface finishing is an important aspect for mechanical parts that are in contact with other components of the machine. Still, the use of AM for spare parts production remains very often too expensive.

(ii) Functioning of the value chain and critical factors

There is no clear value chain of AM for spare parts for machines as only a few cases have been identified with a low maturity level. Only the cooperation between Schunk and Materialise seems to have reached the commercialization phase and a business model has been developed for the on-demand platform of the two companies in that respect. Also particular AM suppliers involved in the production of spare parts for machines have been identified in Western European regions, constituting the first seed of what could in the future become a value chain. The online platform offers companies to replace their gripper fingers with on-demand and tailor-made gripper fingers which would present similar mechanical properties than the original ones thanks to AM. This is the only form of service or product offering that could be identified regarding AM of spare parts for machines. Other forms of AM use for that purpose are either isolated cases (at a rather early stage of development) or are kept secret by companies. Such absence of any value chain makes the identification of relevant regional capabilities difficult: only Belgium, German and Dutch regions fell under the scope of the cases observed so far. With companies such as Schunk, Siemens or Atlas CopCo developing in-house capabilities, it is possible to identify the Baden-Württemberg, Dutch North Brabant and Flanders as key regions. Beyond the issue of surface finishing, the development of the value chain seems to be hampered by issues such as guarantees of the machines or even mechanical properties of the parts produced that might differ from the part to be reproduced.

Cost effectiveness is a major issue for the production of spare parts in general (GAO, 2015). The use of AM for spare parts is most likely to be focused on cases where it adds value. Given the current state of the technology, conventional methods remain more efficient to produce generic spare parts for machines with low value. Therefore, it is suggested to focus on (expensive)[674] machines in which companies invest for long-term mass production. This is the common point between the packaging and automotive sectors: both are involved in mass production.

[673] Source : http://additivemanufacturing.com/2015/08/03/concept-laser-additive-manufacturing-with-a-digital-process-chain-in-the-blok-group/

[674] The fact that the machine is expensive does not mean that the part(s) to be replaced will be more or less expensive.

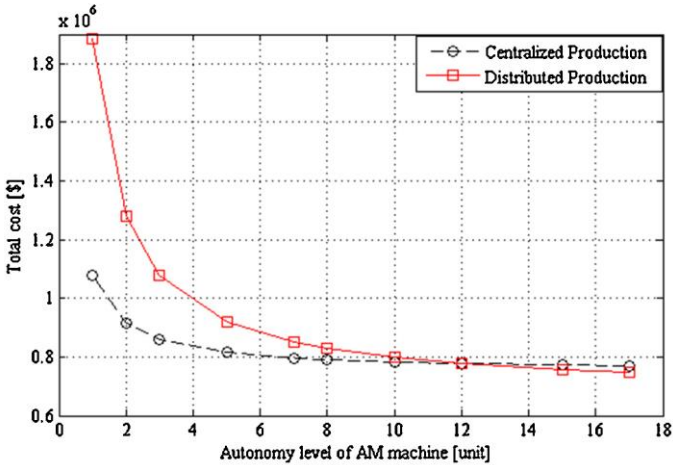
The machines involved in the production processes are usually expensive and expected to function for several decades. Heavy machinery might also be a relevant focus: "*For example, makers of industrial vehicles such as John Deere, NACCO and Caterpillar (all SCRC partner companies) must hold replacement parts for 30-50 years because the vehicles they produce are in service for that long*" (Deshmukh and Handfield, NoDate)

The reason why companies have been less eager to look into AM for spare parts is not only related to the technology. It also relates to the lack of skills and training, as well as some business-related reasons: purchasing managers are for instance constrained by investment decisions, and are more reluctant to adopt new solutions unless they see a good case for savings and efficiency gains. Moreover, should a large company switch over to AM for the production of its spare parts, it should make sure that a distributed network is effectively available to make AM a factor of efficiency gains.

Although most of the existing "spare parts" are currently being produced as part of the regular production process (among non-spare parts), the scenario might differ when coming to specific on-demand cases. For example, when a machine is set to work for a period of 30 to 50 years, it might be that the replacement parts are no longer produced by the supplying company 20 years later. Therefore, on-demand spare part production becomes relevant as the use of a spare part will less likely come during the first year of use of a machine but will rather happen at the end of life of the machine. The replacement of a machine part remains a case-by-case issue as often, there is no serial production of spare parts such as one could observe in the automotive sector (where a spare wheel is for instance part of the overall production and not subject to on-demand 'spare' production). Moreover, in order for spare parts to comply with the machine, the spare part should respond to initial specifications according to which the initial part was produced[675].

According to the interviewees, AM is expected to be beneficial to its users in terms of reducing stocks and warehouses, deliveries (no shipping of the spare parts) and related environmental footprint, delivery times and wasted parts. One of the main barriers facing AM remains the cost associated to the printing of a spare part. However, an alignment between the costs and benefits of AM as to finally allow for distributed production could possibly take place in some industries (see Figure 109). AM of spare parts would also imply lower CO_2 emissions, less shipping (with a focus on the transport of materials), etc. Figure 109 suggests that on a long-term perspective, the economic benefits of AM and the resulting distributed production would counter balance its initial cost of adoption.

Figure 109: Impact of future AM machine automation level on total cost



Source: Khajav et Al., 2013

Deshmukh and Handfield (NoDate) stated that in the future "*OEM suppliers and manufacturers would not require to maintain inventories since the products can be produced immediately with the help of 3D-printers at a lower cost than it would cost for production with traditional processes"* and added that *"For example, Thogus Manufacturing, a custom plastic injection molder, found that for a specialty part, 3D-printing reduced the cost of manufacturing from $10,000 to $600, the build time from 4 weeks to 24 hours and the weight of the object by 70-90 percent*".

675 However, some would foresee the opportunity of improved design (optimization of the part, new functionalities…) which would imply revised specifications.

4.2.6.3 Missing capabilities

(i) Regional dimension and missing capabilities

There is not yet a value chain with clear regional components in the present area. One of the particularities of this case area is that it is very dependent on the sectors to which outputs are being delivered: industrial machines will have very different characteristics depending on the sector in which they are used. As no clear sector can be identified where AM would be raising for the production of spare parts, it appears to be impossible to conceive the value chain at the application level at this very point in time. Multinational companies with global locations did not make their use of AM transparent when coming to spare parts for machines and it is therefore impossible to clearly identify existing capabilities except for specific Western European regions such as Flanders (BE) and Baden-Württemberg (DE).
Besides the case of Schunk's collaboration with Materialise, it was confirmed during the interviews that the printing of spare parts was operated on a case-by-case basis and was perceived as a solution that is not yet fully reliable in companies that are effectively experiencing it for machines' spare parts. A key competence is in this field 3D-scanning. In order to 3D-print a spare part, scanning has to be performed to obtain a 3D-design which can then be corrected, layered and then printed. However, this competence is not missing in Europe as several companies were identified that are active in this area, for instance in the UK. The missing capability is rather at the end of the chain, and more precisely at the level of the finishing and post-processing of the parts. It is indeed known the quality of AM is not sufficient (precision)

Like several others, one of the interviewees belonging to a well-known 3D-Printing printer and service provider explained that the use of AM for machines' spare parts was to be evaluated carefully as it implies very small lots production and can be done with other technologies. This suggests that although the value chain is only emerging, barriers are most likely to hamper its way off the ground.

(ii) Barriers to the uptake and further deployment of AM in the value chain

One of the main critical factors is time. The possibility to reduce maintenance time on machines therefore makes AM attractive to companies. Without specifying which parts or systems were under the scope, an interviewee explained that the multinational he belongs to has business cases where it is possible to reduce logistic and maintenance times by 90% and that this could apply to production machines. Despite of the benefits AM could bring however, the level of demand remains low due to several obstacles.

Knowledge and manufacturing culture

- One of the main critical factor that was clearly identified as a barrier by most interviewees is the one of **skills**. Appropriate training is still missing in engineering and design **curricula**. Skills are therefore not yet in line with the needs of industry.
- Closely related to the skills' issue, th current "***culture***" was also said to be a barrier to the further deployment of AM. AM technologies require different manufacturing approaches compared to traditional ones such as milling. It was therefore concluded that the culture and **current approaches to manufacturing** (and especially in the field of design) were to be re-thought or somehow updated to make AM be used in an appropriate and normalized way.
- More specific to large multinational companies is the **availability of a distributed network** that allows on-site printing of spare parts. AM printers should therefore be available at the location(s) where the industrial machines are.

The cost of AM

- The **cost of AM** was also pointed by several interviewees as a barrier. They usually referred to the cost of AM compared to subtractive (and formative) manufacturing techniques.
- Some interviews indicated that another issue – not only linked to AM – is related to access to finance with relation to advanced technologies: further than the related initial costs of adoption, there is also the difficulty in having financial institutions accepting intangible goods (as ideas or invention) à as a collateral.
- Closely linked to the age of the machines at stake, the **availability of spare parts** is an additional barrier. In case spare parts are available from the machine builder (which are most likely not printed but produced with traditional tooling), then AM appears as a secondary option.
    - One should note that AM is relevant to the printing of spare parts of machines as long as the machines (are expected to) work for a long time period (20+ years). In order to be useful in that respect, digital content (the piece digitally designed in 3D) is to be made available to reproduce the initial (broken or to-be-replaced) component.
- As mentioned in the introduction to this section, **time** is a key critical factor. An interviewee referred to the amounts of money invested in AM which are seen as important investments by purchasing managers. According to the same interviewee, these managers are now expecting to see the returns (for instance in time and cost savings) on the investments made in AM so far before investigating it further.

- Finally, the **structure of the value chain** makes the use of designs to print spare parts difficult[676] for different reasons:
  - Machine suppliers are less likely to provide designs of spares that they could sell themselves;
  - The warranty on a machine could not work anymore should a spare part be printed;
  - There can be important differences between the initial part and the spare one, despite the fact that a scan or initial design could be made available.

Technical barriers

- The **lack of knowledge about the processes** at stake was pointed at as a main barrier to AM deployment. Also **materials** and constraints should be better known. The lack of knowledge limits the development and diffusion of AM technologies in the area but also constitutes a barrier to its adoption as company managers are not aware of its concrete positive and negative characteristics.
- Another barrier is the **gap between classical parts' materials and the current materials used in AM**: both materials are usually different and involve different characteristics. To make this point clearer, one has to make the difference between a part that is produced traditionally with a mold or subtractive technique; and a replacement part that would be produced out of a powder-bed fusion device for instance. A difference between the materials also indicates a difference in the mechanical properties of the part being produced. This implies that AM of spare parts is difficult as the spare parts should respond to the same terms of reference (specifications) that the initial part.
- Finally, the last barrier relates to the **lack of precision of AM** which requires post-processing and the complementary use of other techniques to finish the printer part. This barrier is inherently grounded into materials' properties: for instance, parts made of maraging require thermal treatment. As mechanical requirements require neat surfaces, AM is therefore not the best solution for the printing of metallic (critical) spare parts for machines. There might however be solutions coming up (see Box 49).

Box 49: The post-processing barrier about to be overcome?

Hybrid technologies and the combination of traditional and additive techniques are very often seen as one of the next steps in manufacturing. This is also the case when considering AM for machines' spare parts. As parts to be replaced are very often in contact with other parts, surfacing should lead to a neat end part. In the field of machinery in particular, the surface of every mechanical component is critical and has to be neat to allow for the right moves when put in function. However, AM alone does not lead to the same quality of parts than traditional techniques. Finishing and post-processing are therefore still needed to produce parts with AM. This was identified as a critical issue in the present report. Additional post-processing implies longer production times, more complicated planning, and additional costs.

One of the interviewees from an American University said to be currently developing a solution based on powder-based systems that would also operate automatic finishing. This would be a project in collaboration with private sector companies in the field of machinery. This software solution would be running on top of all other applications and would make use of .amf format (a format aimed at replacing the traditional .stl format used in the field of AM and allowing for more information to be stored in a single file[677] and also evaluated as a joint standard by ASTM and ISO[678]). The software would then allow for reading the CAD file and specify which parts should be subject to finishing. The interviewee explains about one of the companies he works with that "*After 30 years what is left in the warehouse is thrown away (…) in the meantime they pay tooling and storage*". AM would therefore fit but requires better surface finishing. The solution under development comes as to complement what current hybrid systems already do: while hybrid systems usually are limited in the geometries that can be obtained, they are also subject to longer time cycles. For instance when a part is printed, it should cool down before machining can take place. This solution is said to be at a TRL7 stage, coming to the edge of commercialization. It is supported by AmericaMakes and the National Science Foundation (NSF) in the US. Here the difficulty arises to find additional funding in order to bridge the last TRL level as companies are reluctant to publicize IPR, which would be a condition to be part of the project.

[676] One of the interviewee explains that "*there are trademarks on products and spares design. If we consider the chance for our customers to "print" spare parts from their side, this is quite critical point. Spares are important items of the range of products a Company is selling, and normally generates quite good profitability, so I cannot imagine our customers to produce parts by themselves and reduce our profitability. There are also possible issues related to eventual defect in "local spares manufacturing by 3D-printing", and warranty replacement for products, in case a possible failure can be related to wrong printing*"

[677] While the .stl format used to contain geometric data, the new .amf format contains dimensions and tolerance information.

[678] http://www.astm.org/Standards/ISOASTM52915.htm

4.2.6.4 Conclusion: opportunities for public support

Spare parts are being produced for components such as turbine blades and burner tips[679]. However, the value chain of AM to print spare parts for machines is only emerging. Companies are currently testing this formula internally or together with service providers. There is no clear or very limited information about the specific parts and components at stake and companies refuse to disclose any information on the topic due to the strategic value of AM as a differentiating factor. Service providers called upon to produce spare parts do not disclose any information and companies themselves refuse to share about the specifics of the components under the scope, but all agree that the spare parts business is emerging. One of them suggested that 10% of its business was dedicated to spare parts printing, not mentioning whether these parts were aimed for machines or other products.

It was however found that some large multinational companies make use of AM to print spare parts for their internal equipment, including machines. The example of the gripper[680] illustrates the rationale underlying its use as it shows that AM can be used to print parts that are not available anymore or that require some specific design. For instance, an interviewee explained that printing spare parts for machines would not make sense if it was only about reproducing parts: the interest would lie in the possibility of printing a part that has the same functionalities than the original one but that is also optimized, which could prove to be an issue as each part is to comply with initial (original) specifications.
Various interviewees – especially SMEs- suggested public intervention in support of AM knowledge development and accessibility of service centers which could provide AM design related services (CAD files adjustment to STL files) and realize the rapid prototyping of new manufacturing components, further than of machine spare parts and cold molding.

As a first step in the development of this emerging business area is the optimization of spare parts for products which are on the market today. Also repair of these products is being seen as a potential field where AM could add value and lead to savings. Among the upcoming trends, the following are also expected to be observed:

- The constitution of hubs is foreseen: one of the interviewees from a large-scale manufacturing sector explained that his company was now studying the possibility of "hubs" where subtractive and additive devices would be made available to produce spare parts for production machines on site. Setting up such hub would allow reducing the costly time needed to ship each part independently when a machine would break: on a large-scale production line, a delay caused by a machine on hold has terrible effects on the number of units produced and can therefore be very harmful to the business.
- One of the interviewees expects that all metal workshops will at some point make use of AM as one of the elements of their toolbox.
- One of the interviewees referred to air compressors and compellers as possible parts where AM would add value. Water pumps, separators and parts of forging machines were also mentioned by other interviewees. Other parts that can be found on machines are already being printed for household appliances and could be expected to be found on machines in the future.
- As explained by an expert on the topic from a private consultancy, distribution patterns of spare parts are expected to eventually change with AM as stocks will be impacted and transportless deliveries anywhere in the world, what we see is that there will be less spares, more distributed production sites. Also see some parts will not be exchanged for new but will be more possibilities for repair – dramatic effects on the investments along the value change. It will change.
- Finally, an interviewee explained that there was an emerging possibility to sell designs instead of selling parts would open with the (possible) rise of AM in the field. There is however a fear that was expressed by several contacts afraid that designs could be stolen.

Policy implications were identified that directly link to the issue of seeing the value chain emerge and take off the ground. Three main blocks can be put forward for this specific value chain in emergence.

1. R&D support is the starting point and key priority. It could for example take the shape of collaborative/cross-regional R&D support (through grants, R&D co-funding, collaborative R&D projects, networks of infrastructures and one-stop shops):
    a. **Knowledge** is still to be developed about the materials and processes at stake. This knowledge requires further **R&D** support that could emanate from regional, national and European governments.
    b. The on-demand and localized printing of spare parts for machines would be beneficial as it would most likely be more efficient and environment-friendly. It is however limited because of the gap between the relevance of the technology and the quality it can produced. In order to **improve its performance**, **AM needs to be combined with subtractive methods** and **hybrid manufacturing** should be further developed in that sense while taking into account new (competing) developments such as the ones depicted in Box 49.
    c. **Collaborations** could be organised to establish links and relationships between companies from different branches such as additive and subtractive. These collaborations could be supported on

[679] See http://www.siemens.com/innovation/en/home/pictures-of-the-future/industry-and-automation/additive-manufacturing-from-powders-to-finished-products.html
[680] See http://www.materialise.com/press/materialise-empowers-schunk-egrip-an-ordering-platform-for-3d-printed-grippers

key topics (whether business or purely R&D-oriented) and aim towards the development of hybrid systems.

2. One of the interviewees referred to the need for **pilot production and demonstration facilities** where companies would be able to test AM. As companies' resources are limited and expertise is lacking on AM and its integration by firms, public support to such facilities could be brought:
   a. By regional and national authorities funding or supporting existing/new local facilities;
   b. By the European Union to build upon and connect existing/new facilities at the level of the EU28.
3. **Awareness raising** is still to be developed and improved in order to inform relevant company managers about the pros and cons of AM for machines' spare parts. This could be operated at all government levels but coordination would anyway be needed at the European level to ensure homogenized and credible information to be diffused. Dedicated website and events could support such ambition at the EU level.

4.2.7 Lighting and other home decoration products

4.2.7.1 Scoping

(i) Context

Additive Manufacturing (or 3D-printing) offers many possibilities for the production of consumer and lifestyle products and covers amongst others home decoration objects. Items of all fields can be produced by AM, limited only by size and materials. Nearly any printed thing can decorate the home if the owner wants it. AM is expected to have a profound impact on the way manufacturers make almost any product. It might become an essential 'tool' allowing designs to be optimised to reduce waste, products to be made as light as possible, inventories of spare parts to be reduced, products to be personalised to consumers, consumers to make some of their own products, and products to be made with new graded composition and bespoke properties.[681] Many experts see 3D-printing also as an opportunity for highly industrialised economies to slow donw a further de-industrialisation and offshoring of production.[682]

Figure 110: 3D-printing at home for decorating the home

Source: Dezeen Book of Interviews, 2013, http://www.dezeen.com/2013/08/09/we-want-to-put-3d-printing-in-every-home-janne-kyttanen/

[681] See The Government Office for Science (2013) "Foresight (2013). The Future of Manufacturing: A new era of opportunity and challenge for the UK, Project Report", London, UK

[682] See Antoine Blua (2013) "A New Industrial Revolution: The Brave New World Of 3D-printing", http://www.rferl.org/content/printing-3d-new-industrial-revolution/24949765.html

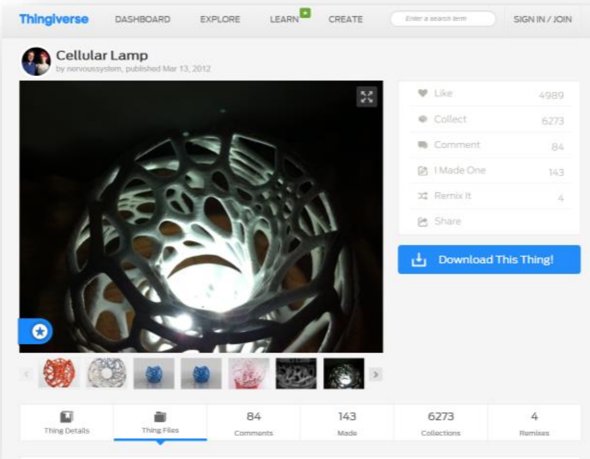
The described application field has a strong open source characteristics. A huge number of designs including 3D data can be downloaded for a certain charge or for free from the 3D-printing community. Networks like 3dhubs.com enable each user at home to create own 3D-printed objects. The following map shows the number of 3D-printing hubs connected to the 3D Hubs network. Europe shows a relative high total number and also a high density of local hubs. The cities with most printers are New York (400), followed by Los Angeles, and followed by London which has currently more than 300 3D-printing locations.[683]

Figure 111: The trend report of 3D Hubs provides a perspective on the 3D-printing community, based on data from the 3D Hubs community. The map represents the geographic distribution of over 25,000 printers on the global platform of 3D Hubs, providing access to 3D-printing in over 150 countries.

Source: 3D Hubs "3D-printing Trends", January 2016, https://www.3dhubs.com/trends

Therefore, the customer can take an active part in the production process. Design and printing platforms enable consumers and designers to develop, produce, and sell their own products. Besides these network approaches scanning, data refinement, and printing services build a major component of the identified value chain in this area. Also the retail of 3D-printers and printing materials is an important pillar of the value network.

Figure 112: Example of an open source design for a 3D-printable lamp



Source: Thingiverse, 2016, http://www.thingiverse.com/thing:19104/#files

[683] Source: 3D Hubs "3D-printing Trends", January 2016, https://www.3dhubs.com/trends

However, the consumer market for 3D-printed home decoration products is still a niche. Today, 3D-printing is less than 0.1 percent of conventional manufacturing in the total services and products made.[684] And due to Gartner's 2015 Hype Cycle report on 3D-printing, consumable products are the one with the lowest expectations of all applications and are still in the stage of "innovation trigger". Consumer 3D-printing is positioned to fall into the "trough of disillusionment" very shortly due to an increase in negative media stories about consumer 3D-printing in recent months, as excited consumers discover that the technology is still not quite in a form usable by them.[685]

Personalization is a very strong issue in this field and 3D-printed products are being developed by companies, designers, and customers themselves.. Examples of most important applications are art objects, vases, sculptures, wall décor, picture frames, furniture (e.g. chairs, tables), and particularly lamps which will be further described in the next chapter.

(ii) Application area: Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others

In the field of home decoration consumer products the customer can take an active part in the development and production process. Design and printing platforms enable consumers and designers to develop, produce and sell their own products. Besides these network approaches scanning, data refinement and printing services build a major component of the identified value chain in this area. In addition, the retail of 3D-printers and printing materials is an important element of the value chain. However the consumer market for 3D-printed home decoration products is still a niche market. Only few companies have been identified building prototypes and selling (small) product series in the application field of home decoration.

This application area of AM is hence so far mainly represented by artists and designers who create prototypes for galleries and also small series of consumer products for at home and also by networks and platforms for private persons creating and printing their own or downloaded designs.

Originally, we searched for each of the identified type of decoration object separately. However, during the search it became clear that each of the 3D-printed home decoration product types only represent a very small application field. The one product type that we identified as the most broadly offered is represented by lighting products. These products are as offered by various producers in Europe using various materials, polymer and polymer composites.

The following figures show some examples illustrating the strength of 3D-printing in the case of lamps. Compared to traditionally manufactured lamps the 3D-printed ones show very interesting forms and light-shadow-effects which in this way have not been possible so far. The first example reveals one identified characteristic of the 3D-printed home decoration items at the moment, i.e. they are either art objects or highly priced high-end designer products.

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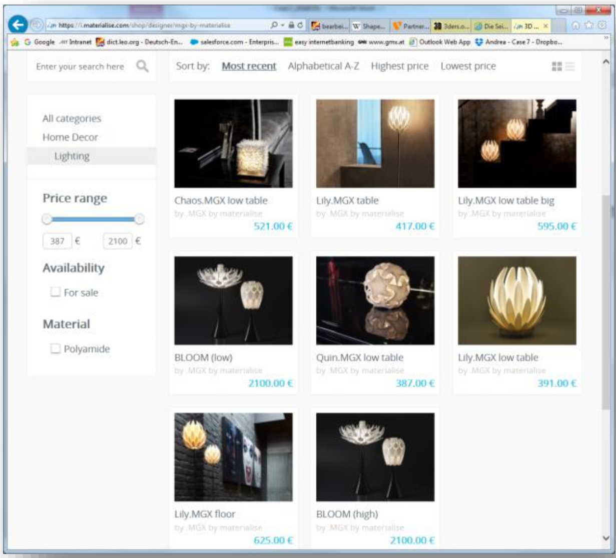
684 See Antoine Blua (2013) "A New Industrial Revolution: The Brave New World Of 3D-printing", http://www.rferl.org/content/printing-3d-new-industrial-revolution/24949765.html

685 See Pete Basiliere (2015) „More On Gartner's 3D-printing Predictions", http://www.fabbaloo.com/blog/2015/8/26/more-on-gartners-3d-printing-predictions

Figure 113: The online boutique .MGX by Materialise offers various highly priced home decoration polyamide lighting products



Source: .MGX by Materialise, 2016, https://i.materialise.com/shop/designer/mgx-by-materialise http://www.gassling.com/

Figure 114: "Biophilia" (left) and "Plüne Applique" (right) are a lampshades of sintered polymer

Source: Exnovo, 2015, http://www.exnovo-italia.com

Figure 115: "Breaking bulbs" is a series of 3D-printed lamps giving the illusion of breaking glass

Source: Gässling, 2015, http://www.gassling.com/

Also other home decoration products such as vases and bowls for example are showing interesting new forms which are very often inspired by nature.

Figure 116: A 3D vase called "The Hidden" made by the biggest 3D-printer in Europe (2013) in Leuven, Belgium.

Source: Antoine Blua (2013) "A New Industrial Revolution: The Brave New World Of 3D-printing", http://www.rferl.org/content/printing-3d-new-industrial-revolution/24949765.html

With concern to furniture, 3D-printing also opens new dimensions for creative designs and new functional material. However, so far only art objects, prototypes, and few design collections have been identified. For example the designer Lilian Van Daal created a 3D-printed soft seat which is designed as an alternative to conventional upholstered furniture, which requires several different materials and processes to create the frame, padding and covers.

Figure 117: Biomimicry chair by Lilian van Daal replaces traditional upholstery with 3D-printed structure

Source: Alyn Griffiths, 2014, http://www.dezeen.com/2014/08/05/biomimicry-3d-printed-soft-seat-chair-by-lilian-van-daal/

Concerning sculptures the identified most popular application of additive manufacturing is 3D-printed portraits and several companies are offering this service in Europe already. One example is shown below.

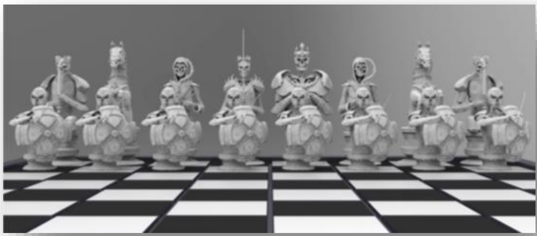
Figure 118: 3d portraits are being offered by several companies, e.g. Fabberlounge[686], 3D Solutions[687], Twinkind[688], and Staramba[689] (also portraits of and with stars)

Source: Fabberlounge, 2016, http://fabberlounge.com

In addition to the presented examples, many other objects can be used as home decoration items such as for example games and toys and also musical instruments. However, their primary purpose is not for decoration. Therefore, these application areas were neglected in this case study.

[686] See http://fabberlounge.com
[687] http://www.3d-solutions.at
[688] http://www.twinkind.com/en/picture-gallery
[689] https://staramba.com/

Figure 119: Many other items, such as for example games and toys (here a chess set by the Indian company DF3D) or musical instruments (here a guitar by the British company customuse) can be used for home decoration but were not regarded here.



Sources: Left: Whitney Hipolite, 2014, http://3dprint.com/13172/df3d-3d-printed-chess-set/
Right: Customuse 2016, http://customuse.myshopify.com/products/necromuse

4.2.7.2 Identifying value chain components

(i) Identification of key players and usage of Additive Manufacturing (AM)

Despite of the well-known large companies involved in AM, few key players have been identified along the considered value chain. Most of the interviewed researchers and material or service providers do not exclude this topic and are willing to establish specific projects or to produce prototypes[690]. However, beside the well-know-companies, several smaller service suppliers and some research consortia no key players were identified. Therefore we regard this application field still very research intensive and with fragmented value chain(s).

In the following we describe the most visible of the identified players in groups according to their positions from basic research to product supply on the market.

For the regarded application further research in all different printing technologies and with all available materials makes sense. However, only technologies and materials with reasonable prices and good enough printing qualities are or will become relevant on the consumer market. Research takes place at the private labs of the printer manufacturers and also in Research Technology Organisations (RTOs), as for example and at University Institutes, and in collaborations (see for example the Additive Manufacturing collaboration mainly between ***Fraunhofer Institute for Laser Technology (ILT)*** and ***RWTH Aachen University***[691]). A rather high number of AM research groups have been identified in Europe and certificate and degree programmes aiming at Additive Manufacturing have been launched in the last years in several universities.[692][693] But the specific application area still seems to be a side issue. However, future developments based on the combinations of new lighting technologies with sophisticated 3D-printing technologies (e.g. 4D printing[694]), which are still in the basic research stadium at the moment, are aiming at larger scale market applications. Philips for example has developed smart home applications for lightings, with Philips Hue products which are controllable via Apple HomeKit and smartphone apps.

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690 Sources: See list of conducted interviews in Annex 14.

691 See https://www.produktionstechnik.rwth-aachen.de/cms/Produktionstechnik/Wirtschaft/Themen/~gwxd/Additive-Fertigung/lidx/1/

692 Some AM leading research organisations are in Germany, e.g. RWTH Aachen University , the Direct Manufacturing Research Center DMRC , a research center of the University of Paderborn, the CRC 814, a collaborative research center for Additive Manufacturing within the University of Erlangen-Nuremberg (FAU), the Fraunhofer Institute for Laser Technology (ILT), the Technical University Hamburg-Harburg (TUHH), the Rapid Technology Center (RTC) at the University of Duisburg–Essen, in Belgium the Product Engineering, Machine Design and Automation (PMA) division of KU Leuven (collaborating with Materialse as industrial partner), or in Switzerland the Institute for Rapid Product Development (IRPD) and the Inspire AG. In the United Kingdom several universities are performing research in AM technologies, such as Loughborough University, Cranfield University, Drexel University, University of Nottingham (Additive Manufacturing and 3D-printing Research Group), University of Sheffield and the Science and Technology Facilities Council.

693 Sources: Gausemeier J. et al. (2013) "Thinking ahead the Future of Additive Manufacturing - Exploring the Research Landscape"; http://www.nanofutures.eu/sites/default/files/HNI_DMRC_Strategy_Study.pdf
European Parliament, Directorate-Genaral for Internal Policies (2015): "Open Innovation in Industry, Including 3D-printing", Study for the ITRE Committee; http://www.nanofutures.eu/sites/default/files/HNI_DMRC_Strategy_Study.pdf
SME (2015) "Universities Involved with Additive Manufacturing" ; http://www.sme.org/universities-involved-with-additive-manufacturing/

694 See http://www.stratasys.com/industries/education/4d-printing-project

Some of these are already 3D-printed[695]. The European Project ***DIMAP***[696] is one example of bundled research in this direction. It focuses on the development of novel ink materials for 3D multi-material printing by PolyJet technology, especially aiming at the development of specific smart lighting applications. Its consortium, among others, includes ***Stratasys*** in the United States as printer manufacturer, ***Philips*** as lighting products manufacturer, ***Cirp*** , as an R&D intensive AM service provider and also some ink producers, such as ***Tiger*** and ***PV Nano Cell***, working for example on single crystal conductive nano-inks. The project is led by the Austrian research company ***Profactor***.

At the moment the most common technologies and materials in the regarded application area are Fused Deposition Modeling (FDM) with the most common thermoplast materials ABS (Acrylnitril-Butadien-Styrol) and PLA (Polylactid) and Powder-based 3D-printing Laser Sintering mainly with Polyamide (but also possibly with other materials, such as Alumide, Titanium, Rubber-like, and Wood). Stereolithography (STM) and Polyjet Technology as Resin-based 3D-printing technologies, with the widest variety of materials and highest precision are still hardly used.[697] Plastic materials are therefore the most common in the considered sector. European players such as ***Somos***[698] (DSM) in the Netherlands, ***Evonik***, ***EOS***, and ***Lehmann & Voss***[699] in Germany and ***Arkema***[700] in France deliver plastic raw materials. Many other raw materials suppliers have been identified in Europe[701] (see also 3dsuppliers.org). For consumer products the value chain is dominated by the large printer manufacturers as key players. Most of them sell their own filaments and there are also a lot of vendors selling printers and raw material, and some also software for the large manufacturers (e.g. ***Creative Tools***[702] in Sweden or ***Dream3D***[703] in the United Kingdom). Most of these large printer manufacturers are found in the United States, such as e.g. ***Stratasys***[704] ***including Makerbot***[705] and ***3D Systems***[706]). There are also several printer manufacturers in Europe but only a few have been identified with substantial size, such as e.g. ***EOS***[707], ***SLM Solutions***[708], ***German RepRap***[709], or ***Voxeljet***[710] in Germany, ***Ultimaker***[711] in the Netherlands, and ***Zortrax*** in Poland[712]).

Software developers are delivering essential solutions for e.g. scanning, data processing and handling and regular advancements. Also here, in the area of consumer products strong players come from the U.S., such as for example ***Autodesk***[713], ***3D Systems***[714], ***McNeel***[715], ***Pixologic***[716], and ***Pinshape***[717]. However, several important European key players were identified, such as ***Materialise***[718] in Belgium, ***EOS***[719] in Germany, or ***Dassault Systèmes*** in France[720]. Also open source software solutions are available on the market, shared for example by companies from the U.S., such as ***Google*** (Google SketchUp[721]) or ***MeshLab***[722]. ***Printelize***[723] is a Poland based company that offers sales and quote automation solutions to the 3D-printing service providers and providing a marketplace for 3D-printing services.

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695 Source: Harpe J. (2014) "Light, Art and hue: Unleashing the beauty of light with Philips Hue 3D-printed luminaires", http://www.newscenter.philips.com/main/standard/news/press/2014/20140328-unleashing-the-beauty-of-light-with-philips-3d-printed-hue-luminaires.wpd#.VrB5_E32bVh

696 See http://www.dimap-project.eu/

697 Sources: https://www.3dhubs.com/trends; http://www.materialise.com/; http://www.3ders.org/3d-printing-basics.html#3d-printer-manufacturers

698 http://www.dsm.com/products/somos/en_US/home.html

699 See http://corporate.evonik.de/de/Pages/default.aspx

700 See http://www.arkema.com/

701 Some other identified raw materials suppliers are (see also in Annex the list of players, their nationalities, and their web pages): 3D Prima (Europe), ColorFabb (NL), cc-products (DE), DAS FILAMENT (DE), Dutch Filaments (NL), eMotion Tech (FR), Extrudr (FD3D GmbH) (AT), fabberworld (CH), Faberdashery (UK), FELIXprinters (NL), Filamentum (NL), iGo3D(DE), Innofil3D BV (NL), KDI Polymer Specialists Ltd. (UK), Nanovia (FR), Neofil3D (FR), Orbi-Tech GmbH (DE), Plastic2Print (NL), ultimaker (NL)

702 See http://www.creativetools.se/

703 See https://www.dream3d.co.uk/

704 See http://www.stratasys.com/de

705 See http://www.makerbot.com/

706 See http://www.3dsystems.com/

707 See http://www.eos.info/

708 See http://www.stage.slm-solutions.com/index.php?index_de

709 See https://www.germanreprap.com/

710 See http://www.voxeljet.de/

711 See https://ultimaker.com/

712 See https://zortrax.com/

713 See http://www.autodesk.com/solutions/3d-cad-software ; https://spark.autodesk.com/

714 See http://www.3dsystems.com/

715 See http://www.de.emea.mcneel.com/

716 See http://pixologic.com/

717 See https://pinshape.com/

718 See http://www.materialise.com/

719 See http://www.eos.info/

720 See http://www.3ds.com/

721 See https://www.sketchup.com/

722 See http://meshlab.sourceforge.net/

723 See http://printelize.com/en/

Providers of services for Additive Manufacturing, such as e.g. scanning, data processing, printing, and surface cleaning are building a substantial part of the value chain and amount of players such as, e.g. ***Pinshape***, ***Thingiverse by Makerbot***[724]***, 3D Systems*** or ***Shapeways***[725] in the United States. Shapeways for example is one of the leading service suppliers. It is a marketplace where users can design and upload their own files, after which Shapeways does the printing. This start-up initially started in the Netherlands as a spin-off of Royal Philips Electronics. Now its headquarter is in New York, with other offices currently being located in Seattle and Eindhoven. Other successful printing services are for example ***Ponoko***[726] from New Zealand (and US), ***Rapid 3D***[727] in South Africa, and ***Imaginarium***[728] in India.[729] In Europe ***i.Materialise*** by Materialise has been identified as one of the leading service suppliers. Other players in Europe are e.g. ***Sculpteo***[730] in France, and ***Voxeljet***[731] and ***Alphacam***[732] in Germany.

In the regarded application area the ***customer*** him/herself is becoming a strong key player, providing own services and designs to other users. This is enabled by internet platforms such as for example ***3DHubs***[733] in the Netherlands and in the United States.

Additionally, the ***Fab Lab Initiative***[734] has to be mentioned. About 600 Fab Labs all across the world are offering 3D-printing services to end users. The first FabLab was founded by the Massachusetts Institute of Technology (MIT). The ***Fab Lab Foundation***[735] was formed in 2009 to facilitate and support the growth of the international fab lab network as well as the development of regional capacity-building organizations. It is a US non-profit organization that emerged from MIT's Center for Bits & Atoms Fab Lab Program. Its mission is to provide access to the tools, the knowledge and the financial means to educate, innovate and invent using technology and digital fabrication to allow anyone to make (almost) anything, and thereby creating opportunities to improve lives and livelihoods around the world. Community organizations, educational institutions and non-profit concerns are its primary beneficiaries. As of September 2015 there were 107 Fab Labs in the US and Canada, and 270 in Europe (565 in the world in total).[736] At the moment in Europe the countries with most established Fab Labs are Italy (64), France (58), Germany (31), The Netherland (28), and United Kingdom (23).[737]

Looking at the very end of the value chain we mainly find designers or design companies showing their art pieces and prototypes at various art exhibitions or museums[738] or offering their exclusive, expensive, and often price-winning design collections in low volumes at online stores (e.g. **Freedom Of Creation (FOC)[739] by 3D Systems** in the United States, ***Purmundus***[740] ***by Cirp***[741] and ***Shape and Form***[742] in Germany or ***Exnovo***[743] in Italy). The FOC Collection is applying localized just-in-time production and short distance distribution logistics. It is commercialized through a global network of distribution partners. The most visible European key player again is Materialise which offers home decoration products within an online shop, called ***.MGX by Materialise***[744] (see also previous chapter for examples). Additionally to their online shops also Exnovo and Materialise have established global networks of local distributors and resellers of their design collections. These networks offers a high number of local design shops for interiors, mainly for furniture and lightings Purmundus, for instance, has established a reseller network covering mainly Germany.

(ii) Composition of the value chain

Based on the insights of the previous chapter and specifically regarding the functioning of the value chain in the described application field, we indentified five different core areas in detail. These are: hardware (printers and raw marterials) producers, software developers, service suppliers, and providers of home decoration products. Additionally there is one future oriented field driven mainly by research labs.

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724 See http://www.thingiverse.com/
725 See http://www.shapeways.com/
726 See https://www.ponoko.com/
727 See http://rapid3d.co.za/
728 See http://www.imaginarium.co.in/
729 Source: http://3dprinting.com/3d-printing-service/#rapid3d
730 See http://www.sculpteo.com/en/
731 See http://www.voxeljet.de/
732 See http://www.alphacam.de/
733 See https://www.3dhubs.com/
734 See http://www.fabfoundation.org/fab-labs/
735 See http://www.fabfoundation.org/about-us/
736 Source: https://www.fablabs.io/labs
737 See https://www.fablabs.io/labs?locale=en
738 See for example the ONE_SHOT_MGX. which is a foldable stool manufactured by selective laser sintering as one complete piece. https://mgxbymaterialise.com/principal-collection/interior/families/mgxmodel/detail/detail/45; for more examples see e.g. https://mgxbymaterialise.com/limited-editions/mgxmodel/list/list
739 See http://www.freedomofcreation.com/
740 See http://www.purmundus.de/home_e.html
741 See http://www.cirp.de/verfahren/rapid-prototyping.php5
742 See http://www.shapeandform.de/
743 See http://www.exnovo-italia.com
744 See https://mgxbymaterialise.com/

The first core area of the value chain (reffered as "1" in the figure) is dominated by hardware producers which are trying to sell their 3Dprinters and filaments to as many as possible companies, designers, and also private customers. To enable private persons at home to make use of an own printer, platforms for the exchange and download of mesh files are (being) established by the printer manufacturers under other names (e.g. Thingiverse by Makerbot, belonging to Stratasys since 2013, U.S./Israel) and by service suppliers (e.g. Shapeways, founded in the Netherlands, now U.S.). The user becomes an important member of the 3D-printing community and is enabled to make own designs, to share or to sell them within the community and to act as a printing hub selling printing services to other users. There are also a lot of vendors selling the printers for the large manufacturers, marked as "retail" in the graphics (e.g. Creative Tools, Sweden).

Software developers (marked as "2") are feeding all other actors and deliver essential solutions for e.g. scanning, data processing and handling and regular advancements (e.g. Autodesk in the U.S., Materialise in Belgium, or EOS in Germany). Some specific software solutions enable customers to create better designs or to get support along the whole process (e.g. Spark by Autodesk, U.S.).

Box 50: Eye on IPR issues

The sector is currently strongly driven by the user communities and new forms of IPR such as Creative Commons or GNU (Open Source Software) are of importance. However, traditional patents and industrial designs are relevant, too. However, IPR issues are no barrier at the moment. Newcomers (e.g. users in platforms) nonetheless often need orientation and have to build up knowledge about the alternative form of licencing and protection (e.g. copyright, creative commons). Both open-source and more proprietary software is being used in that area.

The part of the value chain which is dominated by the service providers is marked with "3". They are offering scanning and printing services to the customers and are therefore also pushing the exchange of designs via internet platforms. The shown arrows point in both directions as the customer can give own inputs to platforms and is able to sell own design and prints. There is a rather strong open source character within the 3D-printing community, an example is the RepRap project[745]. RepRap (Replicating Rapid-prototyper) is a free desktop 3D-printer capable of printing plastic objects and re-printing itself. Most of the Service providers are additionally offering certain specific applications, e.g. 3D portraits or lampshades for example (e.g. Materialise in Belgium). This value chain is strongly connected to software development.

Looking at the few existing applications that are already sold to the customers we find designers or design companies offering their exclusive and expensive designer products (e.g. Freedom Of Creation (FOC) by 3D Systems in the United States , Purmundus by Cirp and Shape and Form in Germany, Exnovo in Italy, or .MGX by Materialise). Lampshades, vases, bowls, sculptures, and furniture etc. having complex forms often with certain qualities which could not have been manufactured classically. This seems to be only a small market at the moment. Only design collections and no mass products could be identified due to high printing costs and low printing qualities which makes surface treatments necessary. A high number of manufacturers and vendors of home decoration products were identified being involved in the value chain as local resellers of the 3D-printed design products.

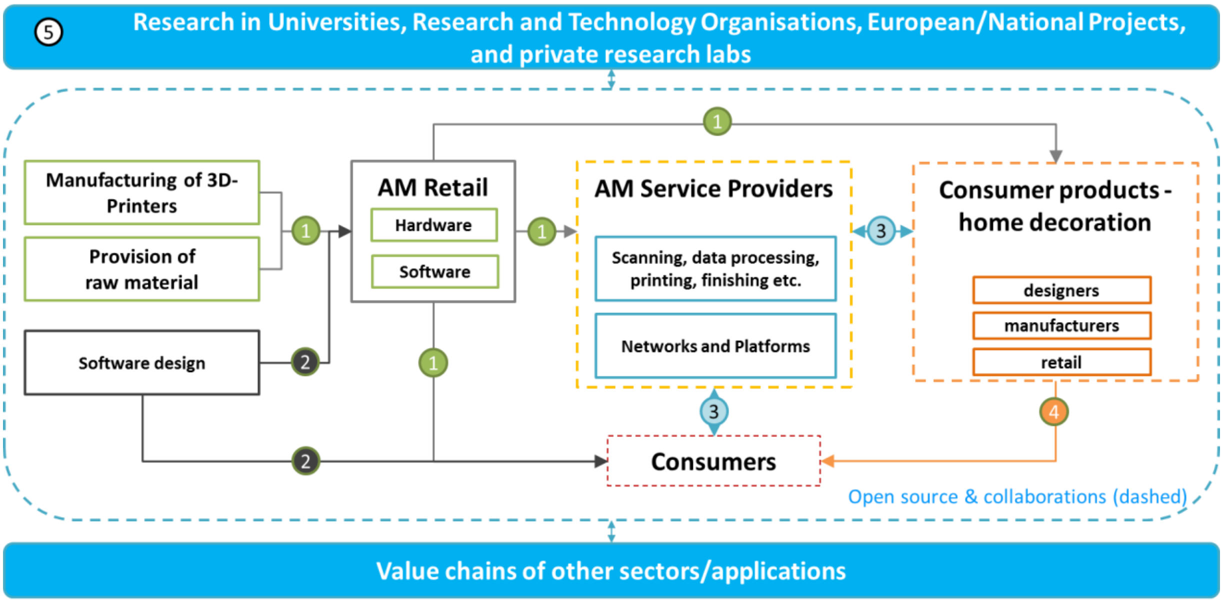
Promising application fields for larger markets seem to be still hidden in research laboratories ("5"). For example, combinations of new lighting technologies with sophisticated 3D-printing technologies (4D printing), which are still in the basic research stadium at the moment, are aiming at larger scale market applications. There is no value chain existing yet but research collaborations have been established and are developing future prototypes. Philips for example has developed smart home applications for lightings, with its Philips Hue products which are controllable via Apple HomeKit and smartphone apps. Some of these are already 3D-printed[746]. The already mentioned European Project DIMAP[747] is one example of bundled research heading in this direction.

[745] Bowyer, A. et al. (2011) "RepRap - The Replicating Rapid Prototyper", Robotica (2011) volume 29, pp. 177–191. Cambridge University Press.

[746] Source: Harpe J. (2014) "Light, Art and hue: Unleashing the beauty of light with Philips Hue 3D-printed luminaires", http://www.newscenter.philips.com/main/standard/news/press/2014/20140328-unleashing-the-beauty-of-light-with-philips-3d-printed-hue-luminaires.wpd#.VrB5_E32bVh

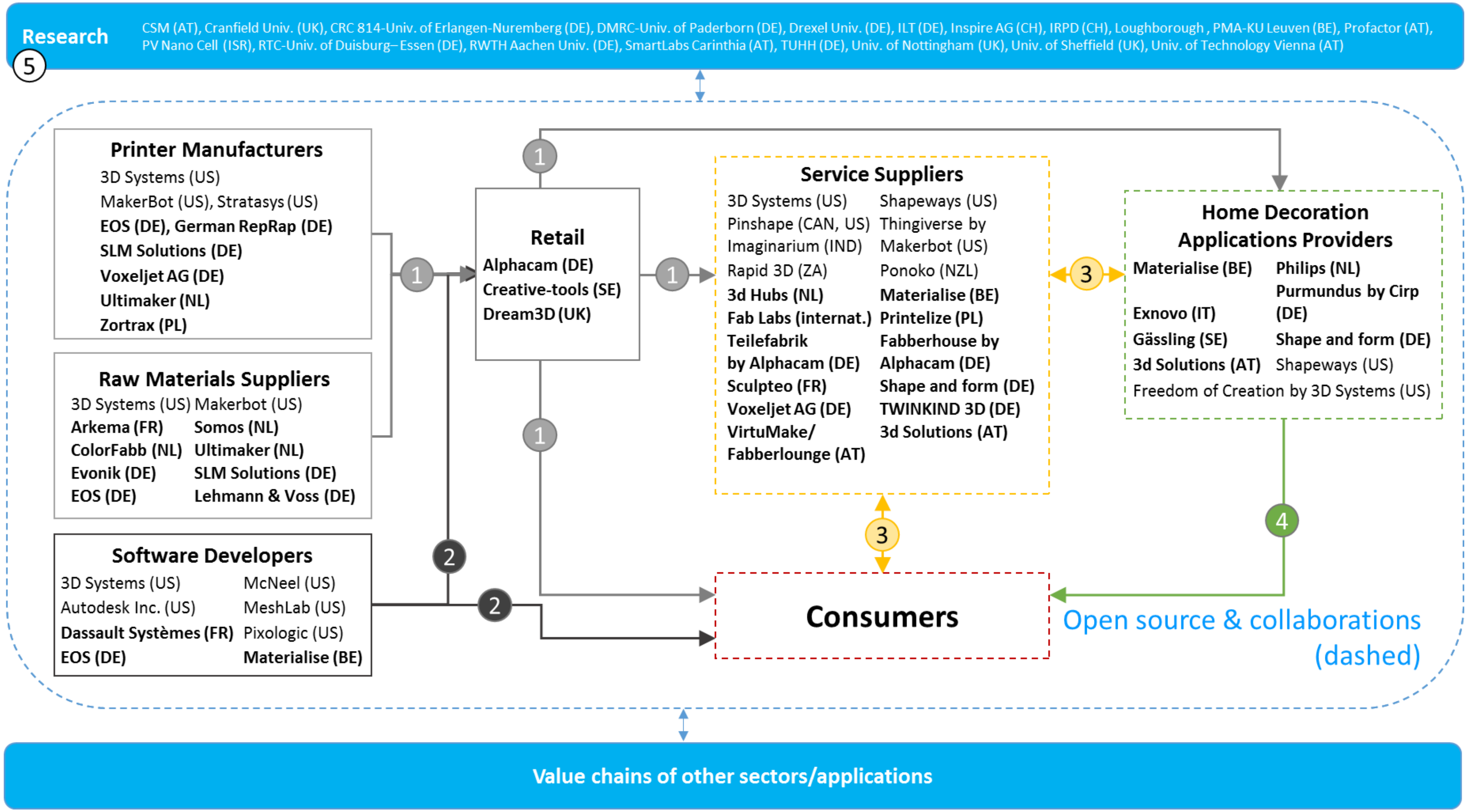
[747] See http://www.dimap-project.eu/

Figure 120: Main segments of the additive manufacturing value chain for home decoration consumer products



Source: Own depiction, 2016

Figure 121: Additive manufactured home decoration products - Illustration of selected key players and their positions in the value chain



Source: Own depiction, 2016

(iii) Functioning of the value chain and critical factors

In this case study players involved in AM of home decoration consumer products have been identified along the whole value chain. Key players in the main elements (research, printer manufacturing industry, raw materials suppliers, software developers, AM service providers, consumer products providers) were identified. The functioning of the value chain was sketched and described and worldwide and European key players were positioned.

We have gained the following insights **for AM home decoration products** based on the previous chapters and the identified sources:

No condensed value chain
For 3D-printed home decoration consumer products the value chain of the involved players is quite fragmented and is intermingling with value chains of other application areas. Hardly any specific value chain for this sub sector was identified, except of certain design collections and their distributors. Designers of home decoration products seem to be actively involved yet. Manufacturer and vendors, however, seem to be involved only as resellers of certain design collections. The market seems not ready for mass 3D-printed products at the moment.

Regarding the services addressing consumers directly the value chain is more condensed. Specific platforms, market places, and networks are enabling end consumers themselves to design, share, sell, and print their own products, many for decoration issues.

High-end products
Only few specific design products and collections in the high-end segment with high prices and small quantities were identified. Home decoration consumer products still have low expectations and need further innovation efforts to enter the market at a larger scale.

It seems that, at present, available and affordable technologies do not offer optimal printing qualities and products often need further surface treatments once manufactured. Also the still quite long production time is a limiting factor.

Looking at the few existing applications that are sold to the customers at present we find designers or design companies offering their exclusive and expensive designer products (e.g. Freedom Of Creation (FOC) by 3D Systems in the United States, Purmundus by Cirp, and Shape and Form in Germany, Exnovo in Italy, or .MGX by Materialise) online or through networks of distributors. These products and product series are mainly lamps, but also vases, bowls, sculptures, and furniture with complex forms often with specific qualities which could not have been manufactured classically. This still seems to be a small niche at the moment.

Consumer Participation
Services which are involving and connecting are generally based on an open source system. Therefore a huge number of designs can be downloaded for a certain charge or for free from 3D-printing communities. Networks like the Dutch 3dhubs enable each user at home to design, share, sell, and print their own objects.

A regional analysis of the involved players has shown besides the actors from the United States some European players are quite actively involved in these collaborative approaches and are building strongly visible communities. For example within the network 3dhubs Europe shows a relative high total number and also a high density of local hubs (see also map above).

The quickly growing Fab Lab Network is another example for successful European participation. In September 2015 Europe counted even more than twice as many Fab Labs than the United States and Canada (107 Fab Labs in the United States and Canada and 270 in Europe).

However, for consumers printing qualities and prices are not totally satisfying yet. Therefore, advancement of printing technologies or new innovations are needed, otherwise consumer 3D-printing might become disillusioned in the future.

Future innovations
3D-printed home decoration products will need further innovations to become able to address larger markets. At the moment we mainly find designer or design companies showing their art pieces and prototypes at various art exhibitions or museums or offering their exclusive and expensive low volume designer products. These are mainly lighting products (e.g. Purmundus by Cirp and Shape and Form in Germany or Exnovo in Italy). The most visible key player Materialise also offers home decoration products within an online shop, called .MGX by Materialise (see also previous chapter for examples). We identified promising research in the lighting area within a consortium where Stratasys and Philips are involved. The combination of new lighting technologies with sophisticated 3D-printing technologies (4D printing), which are still in the basic research stadium at the moment, are aiming at larger scale market applications. Specific and various material qualities will be possible within one printed object, including electric conductivity. There is no value chain existing yet but research collaborations have been established and are developing future prototypes.

Philips for example has developed smart home applications for lightings, with its Philips Hue products controllable via Apple HomeKit and smartphone apps. Some of these are already 3D-printed . The already mentioned European Project DIMAP is one example of bundled research in this direction.

(iv) Regional dimension and missing capabilities

Regarding the necessary capabilities along the value chain from hardware and software development and 3D-printing services to the design, manufacturing, and selling of home decoration products based on the previous chapters (and their sources) we can conclude that Europe is not lacking any of them. However, the capabilities are not bundled specifically in this application area. Players are not equally distributed over the European territory and are mainly concentrated in Western European countries such as Belgium, the Netherlands, Sweden, Germany, France, Italy, and the UK, but also some successful players in Eastern Europe were identified, e.g. in Poland and Slovakia. In Europe most visible key players come from Belgium, the Netherlands, Germany, United Kingdom, Sweden, and France.

Concerning services which are involving and connecting consumers we identified European users as quite active. For example within the network 3dhubs Europe shows a relative high total number and also a high density of local hubs. The cities with most printers are New York (400), followed by Los Angeles, and followed by London which has more than 300 3D-printing locations now.

The quickly growing Fab Lab Network is another example for successful European participation. At the moment in Europe the countries with most established Fab Labs are Italy (64), France (58), Germany (31), The Netherland (28), and United Kingdom (23). In September 2015 Europe counted even more than twice as many Fab Labs than the United States and Canada. We analysed European regions with higher densities of Fab Labs than others in order to identify regions with high end user involvement in 3D-printing.

The following figure shows European regions with high densities of Fab Labs. There is one highly condensed region around the Netherlands comprising the NUTS 1 level regions of NL2, NL, 3, NL 4, BE 1, BE 2, and DEA[748] shows a very high density and total number (more than 40) of Fab Labs. Combined with the insights about key players and their locations gained within this case study we think there is strong evidence for the mentioned region to be a key area within this appclication field. Moreover, .Italy shows regions with high densities of Fab Labs. For example, the small region along the triangle between Milan (6 Fab Labs), Turin, and Lugano comprises twelve Fab Labs. Combining this insight with the locations of the identified vendors of 3D-printed home decoration products we conclude that Italy is significantly involved in providing 3D-printed design home decoration products. These efforts are mainly located around the larger cities, e.g. Venice, Verona, Padua, Modena, Bologna, Florence, Naples, and Rome. In France regions in and around the cities Monaco, Marseilles, Montpellier and Paris show high densities of Fab Labs and in Spain the agglomerations around Madrid, Bilbao, and especially Barcelona (8 Fab Labs) can be mentioned. However, as also seen in the figure, European Fab Labs are concentrated in Western Europe, Eastern Europe is not really involved in building Fab Labs.

Regarding Eastern Europe we conclude that specific barriers exist for these countries.[749]

- Small market for expensive designer products
- Few players
- Little consumer participation
- Lacking knowledge

Eastern European companies are part of the value chain, however, only few companies have substantial size already. The rather late introduction of 3D-printing technologies in Eastern Europe[750] causes a delay in participation. However, there do exist important players in Eastern Europe, as for example Printelize in Poland as mentioned in the previous chapters. Poland was identified as rather active in 3D-printing. There are several printer manufacturers (Zortrax, Monkeyfab, 3DGence, Tytan3D) and distributors (Get3D, CadXpert, Printila) in Poland.[751] The Czech Republic and Latvia has several companies, too, for example the Czech Republic-based 3DFactories[752] or the Latvian 3D-printer manufacturer Mass Portal[753] producing 3D-printers usable for consumer products.

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748 Source: Eurostat (2013) Regions in the European Union, Nomenclature of territorial units for statistics NUTS 2013/EU-28; http://ec.europa.eu/eurostat/documents/3859598/6948381/KS-GQ-14-006-EN-N.pdf/b9ba3339-b121-4775-9991-d88e807628e3
NL2 = OOST-NEDERLAND, NL3 = WEST-NEDERLAND, NL4 = ZUID-NEDERLAND, BE1 = RÉGION DE BRUXELLES-CAPITALE/BRUSSELS HOOFDSTEDELIJK GEWEST, BE2 = VLAAMS GEWEST, DEA = NORDRHEIN-WESTFALEN

749 Sources: http://3dprintingindustry.com; Fab Lab Foundation (2016); http://www.fabfoundation.org/fab-labs/

750 See also http://3dprintingindustry.com/2015/12/11/eastern-european-leader-introduces-3d-printing-baltic-countries/

751 Source: https://3dprint.com/34332/cd3d-best-3d-printing-2014/

752 Source: http://www.3dprinterworld.com/article/3dfactories-launches-profi3dmaker

753 Source: http://3dprintingindustry.com/2014/12/09/latvias-mp-delta-3d-printer/

Figure 122: Map of Fab Labs, showing the European high density regions

Source: Fab Lab Foundation (2016); http://www.fabfoundation.org/fab-labs/

In order to summarize the critical points from what has been mentioned we want to highlight that:

- Few specific design products and collections in the high-end segment with high prices and small quantities were identified.
- Home decoration consumer products still have low expectations and need further innovation efforts to enter the market at a larger scale.
- Printing qualities are still not sufficient for small objects and products often need further surface treatments after printing.
- Long production time is a limiting factor.
- Europe does not lack any more capabilities than the United States because the mentioned technological limitations and innovation needs seem to be valid also for the U.S.
- However, many important key players, especially most of the large printer manufacturers, come from the United States and also several European buy-outs have taken place. Therefore, one of the major driving forces within the value-chain, comes from the United States addressing all users of 3D-printing technologies, and also strongly customers at home.
- To enable these home users for their own 3D-prints, platforms for the exchange and download of mesh files are (being) established by the printer manufacturers under other names (e.g. Thingiverse by Makerbot, belonging to Stratasys since 2013, U.S.) and by service suppliers (e.g. Shapeways, founded in the Netherlands, now U.S.). Regarding the relatively high involvement of European users (see e.g. Fab Labs or 3D Hubs) such platforms could possibly bring specific opportunities for Europe. However, as mentioned, printing qualities and prices are not sufficient yet. Therefore, advancement of printing technologies or new innovations are needed otherwise consumer 3D-printing might become disillusioned in the future.
- Eastern European companies are part of the value chain, however, only few companies have substantial size already and general knowledge on 3D-printing, its technologies, materials and possible applications is lacking in these regions.

(v) Barriers to the uptake and further deployment of AM in the value chain

For a future strategic development of the value chain the following barriers have to be overcome.

Knowledge

Knowledge on the AM process, materials, applications, and actors is important within the value chain to overcome barriers.

- AM processes are currently further developed, e.g. 4D printing is a promising research field for future applications.
- Knowledge on materials and their distinct qualities is partly lacking, e.g. concerning toxicity of printing materials and final products. This issue is also very relevant for consumer 3D-printing.
- Knowledge on final product qualities are often missing. Very often products are single prototypes or small designer series in this application field, e.g. stress tests for furniture.
- Knowledge on the variety of applications that can be realized with current 3D-printing technology is lacking. Experimentation, protoyping, and testing are expensive, especially in the application field of consumer products for home decoration, where in many cases single designers or small design companies are developing the AM products.

Technology performance, materials and finishing

Technological innovations concerning the 3D-printing process are needed in order to raise printing qualities and reduce the need of post-printing treatments depending on the used materials.
Technological advancements, e.g. 4D printing, which will be delivering definable and varying material qualities, including electronic qualities, within one printed object, will open potential application fields for consumer products, especially for lighting products.

- Reducing the production time and cost significantly could open the regarded application for larger markets.

Information and awareness

Information and awareness are necessary for two reasons: first, streamlined information is needed for any innovation system to work efficiently. Second, awareness is needed for managers to be able to overcome their own risk-avoidance behaviors:

- Awareness on AM must be raised, especially within Eastern European countries (as identified within the interviews).
- Quality information is an issue that hampers the uptake of AM.
  - Research activities are one possibility of quality information exchange. These mostly take place within universities and companies. Only few comprehensive activities were identified in form of working groups or project collaborations.
  - Information is also exchanged through platforms and media on 3D-printing. However, the specific interests of actors limit the general quality of information very often.
  - For consumer 3D-printing it is extremely necessary to provide quality information on the chances and limits of current 3D-printing applications in order to avoid disappointments and negative dynamics.

4.2.7.3 Conclusion: opportunities for public support

As concluded previously, for 3D-printed home decoration consumer products the value chain is quite fragmented and based on and intermingling with value chains of other application areas. Hardly any specific value chain for this application area was identified, except of certain design collections and their distributors. Designers of home decoration products seem to be actively involved in the chain yet. Manufacturer and vendors, however, seem to be involved only as resellers of certain design collections. The market seems not ready for mass 3D-printed products at the moment. Regarding the services directly involving and addressing consumers the value chain is more condensed. These platforms, market places, and networks are enabling end consumers themselves to design, share, sell, and print their own products, many for decoration issues.

Only few specific design products and collections in the high-end segment with high prices and small quantities were identified. Home decoration consumer products still have low expectations and need further innovation efforts to enter the market at a larger scale. It seems that at the moment with the available and affordable technologies printing qualities are still not sufficient and products often need further surface treatments after printing. Also the still quite long production time is a limiting factor. These products and product series are mainly lamps, but also vases, bowls, sculptures, and furniture with complex forms often with specific qualities which could not have been manufactured classically. This still seems to be a small niche at the moment.

Services involving and connecting consumers mostly have a strong open source character. Therefore a huge number of designs can be downloaded for a certain charge or for free from 3D-printing communities. Networks like the Dutch 3dhubs enable each user at home to design, share, sell, and print their own objects. A regional analysis of the involved players has shown that besides those from the United States also European players are quite actively involved in these collaborative approaches and are building strongly visible communities.

However, for consumers printing qualities and prices are not totally satisfying yet. Therefore, advancement of printing technologies or new innovations are needed otherwise consumer 3D-printing might become disillusioned in the future.

3D-printed home decoration products will need further innovations to become able to address larger markets. The combination of new lighting technologies with sophisticated 3D-printing technologies (e.g. 4D printing), which are still in the basic research stadium at the moment, are aiming at larger scale market applications. Specific and various material qualities will be possible within one printed object, including electric conductivity. There is no value chain existing yet but research collaborations have been established and are developing future prototypes.

Based on the previously defined gaps in competencies and barriers for the uptake and deployment of AM in the area of home decoration consumer products the following key priority action areas can be defined:

1. **Supporting technological advancements and future innovations:** Home decoration consumer products still have low expectations and need further innovation efforts to enter the market at a larger scale. Printing qualities are still not sufficient for small objects and products often need further surface treatments after printing. Long production time is a limiting factor. Technological advancements, e.g. 4D printing, which will be delivering definable and varying material qualities, including electronic qualities, within one printed object, will open potential application fields for consumer products, especially for lighting products. For user-dirven 3D-printing, advancement of printing technologies or new innovations are also needed otherwise consumer 3D-printing might become disillusioned in the future. AM technical limitations and missing knowledge imply that further R&D has to be conducted with relevant co-investments from the public sector (at regional, national and EU levels) for areas such as:
    a. AM processes;
    b. Material properties;
    c. Quality monitoring, control and detection systems;
    d. Toxicity, explosivity and broader health impacts of used materials;
    e. Reduction of production time and cost.

2. **Supporting specific regional collaborations:** Potential key regions with high concentrations of involved end users and vendors of 3D-printed home decoration products were identified (e.g. Netherlands/Nordrhein-Westfalen, in Italy, South France, and in Spain). Networking activities, knowledge exchange platforms, and other actions could support local players and raise common awareness.

3. **Supporting user platforms:** Regarding the relatively high involvement of European users (see e.g. Fab Labs or 3D Hubs) within 3D-printing platforms, specific opportunities for Europe could be supported financially and with specific actions, e.g. establishing initiatives such as Fab Labs, especially in Eastern European countries.

4. **Development of testing, finishing, post-treatment and demonstration capabilities.** These capabilities could be networked accross regions involved in the different areas under the scope from research to commercialisation, involving RTOs, companies, etc.

5. **Creating new curricula on 3D-printing:** Generating knowledge and raising awareness on AM process, materials, applications, and actors, especially in Eastern Europe.

6. **IPR helpdesks** and **IPR support** from the public should also cover new forms of IPR such as creative commons, rules concerning open source software development, etc.

7. **Supporting prototypes and experiments:** So far, designer prototypes for new applications are rather expensive and have to be financed by the small design conpanies or single designers in most cases. Supporting the development, production, and systematic testing of prototypes in new application areas of consumer products for home decoration, as e.g. surface elements for wall decoration, could help to reduce innovation barriers.

4.2.8 3D-printed textiles

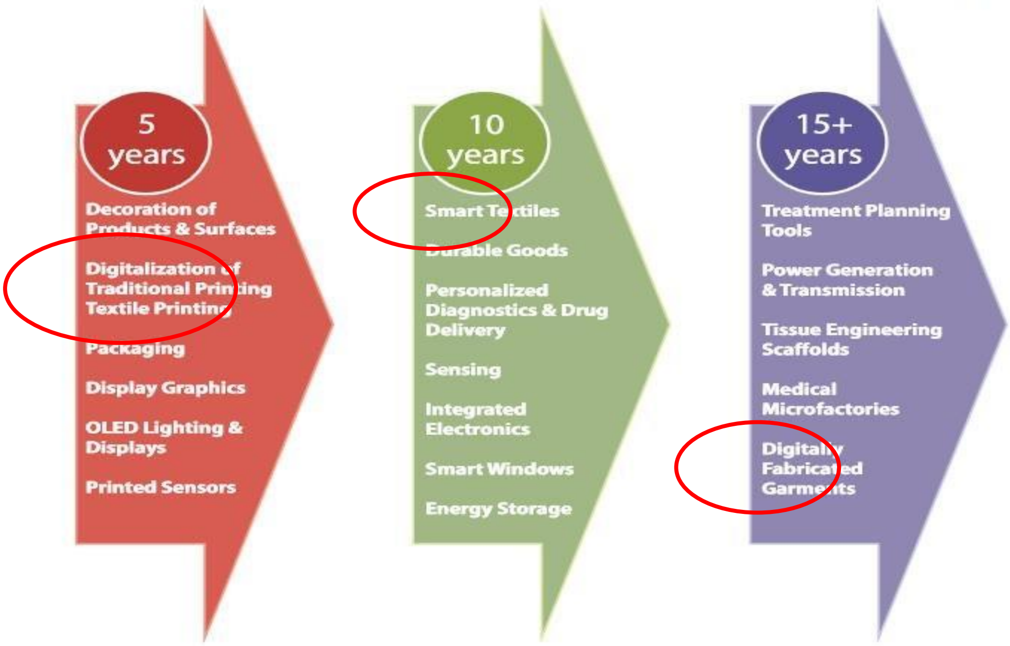
4.2.8.1 Scoping

(i) Context

While 3D-printers are already used in several fields by companies and individuals, printing of textile-like patterns is still rare. In technical textiles, 3D-printing has already been used to create applications such as flexible heating systems or wearable technology. In design garments such as bikinis, complete dresses or shoes are 3D-printed. These garments, however, are clearly produced for show and demonstration, not for everyday wearing.[754] Applications focus on the combination of 3D-printed elements with textiles, e.g. as for shoes, where the sole is printed and then fixed to the upper part.

This case study focuses on technologies that are foreseen to be realised within the next 5-10 years or are already on the market. Diginova, a consortium of European companies and universities, has proposed a roadmap (see Figure 1) in 2014 for how the manufacturing industry could fully benefit from the digital era over the next two decades. According to this vision, we are moving towards manufacturing highly customizable, on-demand goods that are locally produced from raw materials and globally distributed digital designs. An outlook of areas in which digital fabrication could have the greatest impact was summarized within the Diginova project and is depicted in Figure 124. This could lead to extreme product customization, decentralization of production and, perhaps surprisingly, much lower costs of everyday goods ranging from smartphones to medicine.[755]

Figure 123: Roadmap of "What digital fabrication could achieve over the next 20 years"

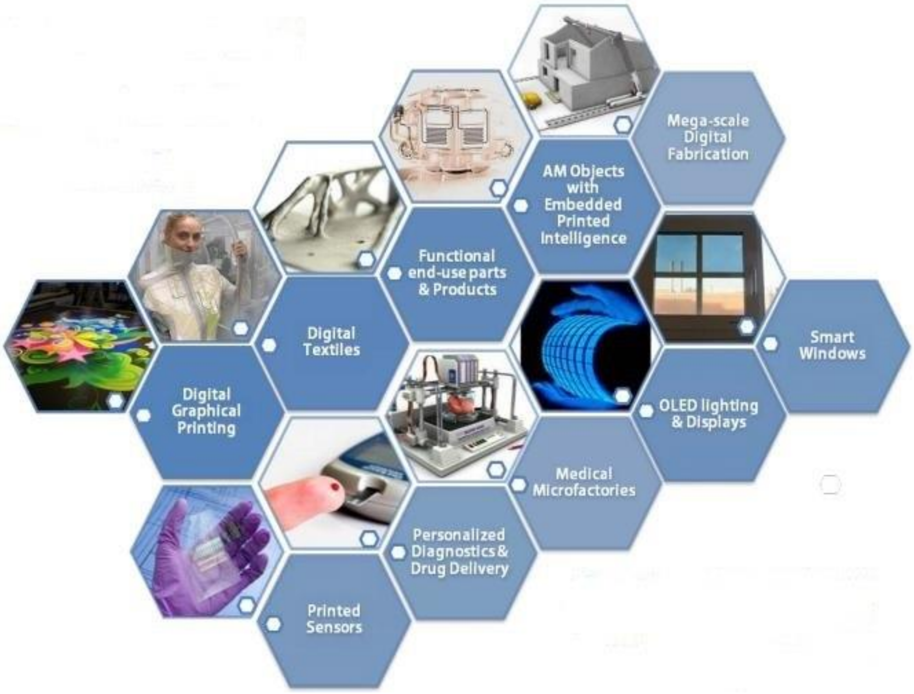


Source: Diginova

For application of 3D-printing of textile one has to distinguish between *3D-printing of textile structures* on one side and the *combination of textile material with 3D-printed items* on the other side, being either *directly printed on the textile or bonded with it* by other matters e.g. agglutination.

[754] see Melnikova, R. et al., (2014).
[755] see http://www.gizmag.com/digital-industrial-revolution/31520/

Figure 124: The areas in which digital fabrication could have the greatest impact



Source: Diginova

Limiting factor at present for printing of textile-like patterns is on the one hand insufficient mechanical properties of pure printed 3D products, when compared to products derived from common technologies such as weaving or knitting. On the other hand the fact that textile CAD data for the creation of textiles produced through additive manufacturing needs to be adapted to the applications. In addition, 3D-printing faces the boundaries that when mimicking textile structures like woven or knitted fabric the space between the single "threads" need to be distinct so that a moveable structure is obtained. Thus the limitation is the resolution of the 3D-printers.

However, while 3D-printing of textile structures faces its boundaries, is not able to replace conventional fiber-based textile production yet and can still be regarded as a small market for designers (with the exception of Tamicare) 3D-printing on textiles to add additional features and functional structures offers interesting possibilities for customized production, important for instance for protective clothing or sportswear. As Fused Deposition Modelling is the most inexpensive method and furthest developed for private use or small companies, it is the method most often used for direct 3D-printing on textiles. Developments of research institutes (see list of interview partners in section 4.2.) therefore concentrate on this technology despite it has lower resolution[756]. Markets include the high-performance textile market, the smart or intelligent textile market as well as customised sportswear or protective clothing. Industrial textiles with special drapings or hooks for e.g. curtains or buildings are another possible application area.

Key issue for the successful combination of 3D-printing with conventionally produced textiles is the knowledge of bonding effects between the different materials, which is achieved through combination of materials and printing parameters or by simply gluing the 3D object to textile structures. The functionality of the added item has to be maintained throughout the lifetime of the textile, despite repeated washing, drying cycles or mechanical stress. A lot of research is going on within Europe (see list of interview partners and key players in section 4) to build up knowledge of combination of different parameters, such as printing conditions or materials, that can be combined, while at the same time the development of new materials and 3D-printers is progressing fast (e.g. Colorfabb; CC-Products; plastics2print; Recreus).

Another issue, where research is focused on, is the fact, that 3D-printing is not an in-line process yet. However, developments in this field are also happening very fast and as there is enough interest from industrial side production on a larger, in-line scale may happen very soon.

[756] Melnikova, R. et al. 2014 and interviews

A short summary of future possibilities and necessary development is given here:

- More suitable filament materials are and will be developed;
- Developments in CAD software and hardware are proceeding;
- Research into adhesion between 3D-printed material and substrate (textile material) needs to be conducted;
- Development and integration of technology into in-line production processes;
- Linking design and end user need; and
- Smart and functional textiles.

3D scanning can be used to design individual 3D models of each customer. These modes can either be printed out as full size dress forms or used as virtual model to connect to individual 2D textile cuts. Software for this is developed e.g. at the Hohenstein Institute in Germany[757], however, this sector of 3D scanning will not be further described in this study.

Applications, which are most promising or furthest in TRL, are presented in the next section. Key applications will be within consumer products (clothing, shoes and accessories) and textiles where (smart) components will be printed on or combined with textile material using AM methods (direct printing on textile materials) or are a combination of production techniques (e.g. sports shoes or protective clothing). This type of functionalisation may also be interesting for interior textiles: e.g. curtains with printed structures, integration of winding systems, hooks and or weights), but this sector will not be discussed in this study. 3D-printing in connection with Electronic Textiles is another application area that is briefly described in the following section.

When identifying and describing the value chain in chapter 2 we will focus on the application in textile printing and design and on shoes and protective clothing.

(ii) Application areas: 3D-printed textiles

1. Application area: Textile Material Printing, Design and Accessories

Computer Aided Design (CAD) is an essential component for the creation of 3D-printed textiles. Despite helping to reduce product development time, the creation of highly detailed, 3D-printed textile CAD data can often be over-demanding for conventional CAD software and hardware systems - resulting in inefficient and time-consuming activities. To create such complex 3D-printed textiles there is a requirement to ensure that there is a sufficient level of separation between individual elements. In addition, when generating conformal garments there is a need to "map complex 3-D geometries to a mesh structure". Furthermore, the collapse of the 3D-printed structure needs to be controlled and calculated, thus optimizing the manufacturing of the textiles.[758]

Jiri Evenhuis[759], an industrial designer from the Netherlands, invented the world's first 3D-printed fabric in 1999 and shortly thereafter co-founded "freedom of creation", a company that pioneered in 3D-manufacturing. These textiles designed by Jiri Evenhuis and *Janne Kyttanen* in 2003 are selected for the permanent collection of the MOMA, New York and the dress can be downloaded and printed from the *cubify*-website (now 3DSystems).[760] These textiles are printed in one go, of course many different patterns can be created using rapid manufacturing techniques (Figure 125) and including different closure systems.

Figure 125: Examples of 3D-printed textile structures designed by Jiri Evenhuis and Janne Kyttanen

Source: *http://www.freedomofcreation.com/home/foc-textiles-to-permanent-collection-at-moma*

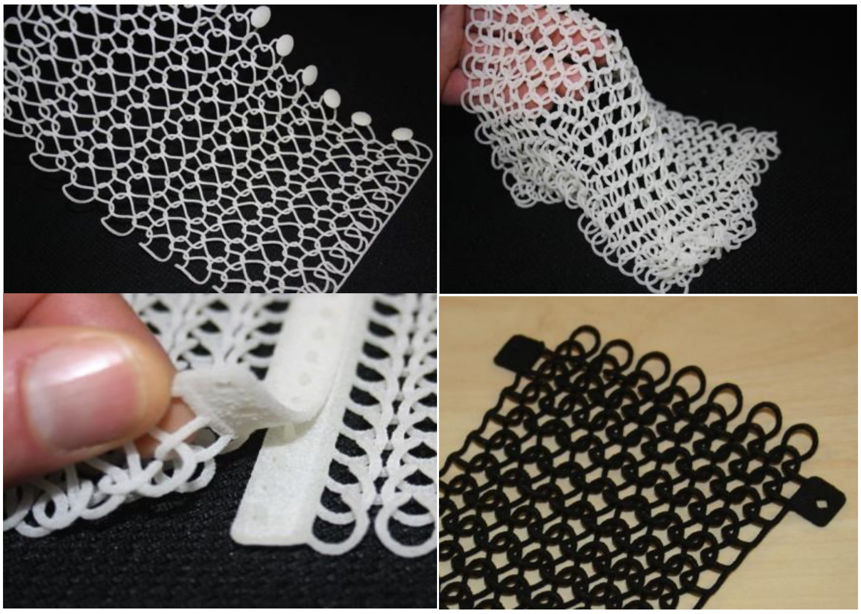
757 http://www.hohenstein.de/en/inline/projectdetail.xhtml?researchProjectFilter.file=%2fmedia%2fforschungsprojekte%2fVirtuelle_3D_Modelle_IGF_18223BG.xml&applicationArea=283

758 Bingham, G. et al. 2007 & 2013; Melnikova, R., A. Ehrmann, et al. (2014)

759 http://jiri.nl/

760 http://cubify.com/store/fashion, now: http://www.3dsystems.com

Figure 126: Examples of 3D-printed textile structures and possible closures from Saxion University



Source: Ir. Ger Brinks Saxion University of Applied Sciences Enschede, The Netherlands

Printing of textile structures is however limited to the resolution of CAD programs and 3D-printers used, as well as to the properties of printable materials. In order to achieve wearability of textiles there is a need for flexibility, which can be gained through the application of flexible material or through structure of the printed textile. Limitations for the latter are the resolution of the printers, as printed threads cannot be printed below a certain wall thickness and with a certain clearance between surfaces, in order to create moveable separate items. Thus printing of textile structures remains at present at a level of research or fashion design resulting in very rigid materials connected through hinges or mimicking kinematic structures (e.g. the kinematic dress by *Nervous System* that has 2,645 interlocking panels 3D-printed as a single computationally folded piece[761]).

However, closest to textile materials come inventions regarding 3D-printing of textiles from *Tamicare* and *Electroloom*. Developed by UK-based Tamicare[762], the Cosyflex^{TM} fabrics are 3D-printed directly from cellulose fibers, cotton fibres and Vytex natural rubber latex (NRL liquid latex) to make a fabric that can be used in disposable panties, with potential applications as compression bandages, sportswear and other products (Figure *127*). Depending on the end-use, various types of polymers, such as natural latex, silicone, polyurethane (PU) and polytetrafluoroethylene (PTFE), as well as a range of textile fibres, such as cotton, viscose and polyamide (PA), can be used to tailor-make fabrics, as the company states. For the feminine hygiene market, an absorbent pad, also made by Tamicare, is moulded within Cosyflex to create a "sandwich construction" panty. The fabric is also said to be breathable, soft and comfortable, dyeable, able to be made into any pattern, natural, made from sustainable resources and fully biodegradable, 3D-printing allowing production without any cut-off waste material. The process itself and the material are patented, with 22 patens filed in Espace Net Patentdatabase[763], two examples are given in the references in section 4. Tamicare is also working with researchers at the Nonwovens Innovation & Research Institute at the University of Leeds, UK.

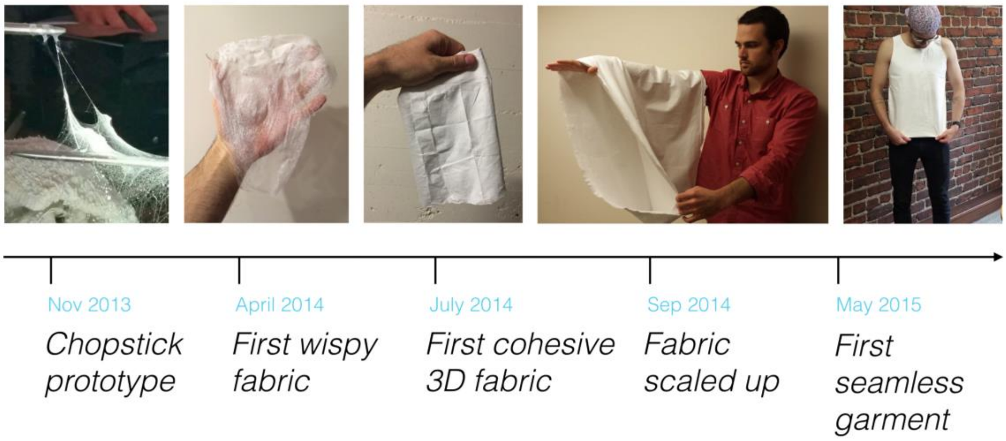
761 http://n-e-r-v-o-u-s.com/projects/sets/kinematics-dress/
762 http://www.tamicare.com/
763 http://worldwide.espacenet.com/searchResults?submitted=true&locale=en_EP&DB=EPODOC&ST=advanced&TI=&AB=&PN=&AP=&PR=&PD=&PA=tamicare&IN=&CPC=&IC

Figure 127: Tamicare: Cosyflex 100x magnification; Cosyflex with unlimited colour options; 2 sample applications of Cosyflex material

Source: www.tamicare.com

Electroloom, a startup company in the US, uses an electrospinning process to convert liquid solutions of polyester/cotton blend into solid fibers which are then deposited onto a 3D mould to create seamless, ready-to-wear garments based on custom 3D geometries. This process is referred to as Field Guided Fabrication, or FGF. New material is tested to achieve strechability and elasticity, also to use different materials like silk or acrylic blends. However, the garments are not washable, but a lot of work is done to improve functionality and wearability.[764]

Figure 128: Electroloom Fabric Progress



Source: https://medium.com/electroloom-blog/a-year-in-review-463fc6397cde#.41xk3rw27

[764] http://www.electroloom.com/ and https://www.kickstarter.com/projects/electroloom/electroloom-the-worlds-first-3d-fabric-printer/description

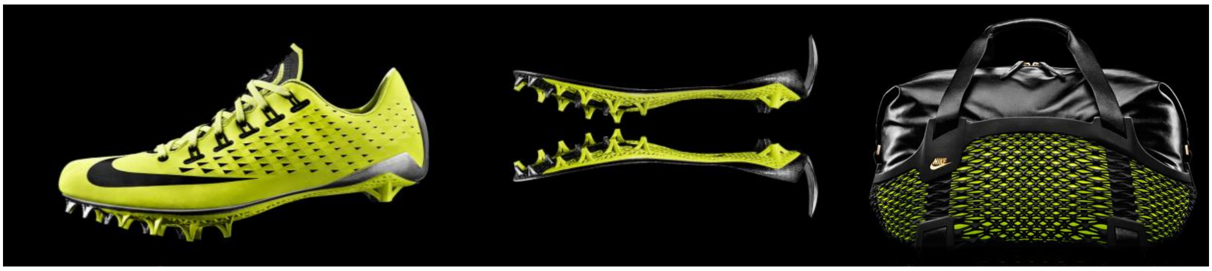
2. Application area: Shoes, Sportswear and Protective Clothing

As **shoe manufacturing** is a labour-intensive business. As shoe technologies continue to evolve, particularly athletic shoe designs, the number of shoe pieces added together has increased, requiring increasingly complicated manufacturing steps to produce shoes[765]. Behind the scenes, 3D-printing has the potential to drastically shorten the supply chain—and therefore slash costs—for the shoe companies[766]. Furthermore personalized sport shoes, that fit the special needs of an athlete, are seen as a vision of sports equipment companies. 3D-printing is seen as a step towards realizing this vision in the very near future, not only for professional but also amateur sports.

Nike debuted first in 2013 with the first-ever football cleat built using 3D-printing technology. The plate of the cleat is crafted using Selective Laser Sintering technology (SLS). SLS is a manufacturing technique that uses high-powered lasers to fuse small particles of materials into a three-dimensional shape. Through proprietary material selection, Nike was able to prototype a fully functional plate and traction system within a fraction of the traditional timeframe and at a fraction of the weight. The SLS process allows for the engineering and creation of shapes not possible in traditional manufacturing processes. It also provides the ability to make design updates within hours instead of months to truly accelerate the innovation process to never seen speeds[767]. Following the shoes a special sports bag as well as shin protectors were designed for players taking part in the FIFA World Cup 2014 (Figure 129). Nike furthermore filed several patents on printing, especially 3D-printing or "additive color printing" as US and worldwide patents (e.g. WO 2014/015033 A2 direct printing on fabric; US9114625B2 Additive color printing). Patent WO 2014/015033 A2 describes a method to directly print on the shoe's upper material before assembling the shoe.

In autumn 2015, both *Adidas* and *New Balance* have advertised "3D-printed shoes". Both of them offer shoes with soles 3D-printed of elastomeric material, the sole is then fixed to the upper part of the shoe. New Balance was working with designer Team *Nervous System* using DuraForm® Flex TPU by *3D Systems* and SLS technology (Figure 130); Adidas "Futurecraft 3D" - Figure 131 – was using the same printing technology in partnership with European firm *Materialise*, but do not mention which material they are using[768].

Figure 129: Nike sports equipment with 3D-printing technology



Source: *http://news.nike.com/news/nike-debuts-first-ever-football-cleat-built-using-3d-printing-technology* *and* *http://www.dezeen.com/2014/06/08/nike-3d-printed-sports-bag-fifa-world-cup-2014/*

765 US-patent US 9155357B2 "Automated Strobel Printing"

766 http://fortune.com/2015/12/15/3d-printed-shoe-race/

767 http://news.nike.com/news/nike-debuts-first-ever-football-cleat-built-using-3d-printing-technology
http://www.dezeen.com/2014/06/08/nike-3d-printed-sports-bag-fifa-world-cup-2014/
http://www.digitaltrends.com/cool-tech/nike-patents-3d-printed-shoe-technology/#ixzz3xbANOOR4

768 http://www.newbalance.com/article?id=4041
http://blog.adidas-group.com/2015/10/a-step-into-the-future-3d-printed-sports-shoes/

Figure 130: Midsole from New Balance by Nervous System

Source: *http://www.newbalance.com/article?id=4041*

Figure 131: Futurecraft 3D by Adidas

Source: *http://www.adidas-group.com/en/media/news-archive/press-releases/2015/adidas-breaks-mould-3d-printed-performance-footwear/*

Personalization is the upcoming trend in shoe design and printing of individual parts. US company *Sols* is producing 3D-printed custom insoles, that can be ordered online by simply following easy instructions of an app and uploading pictures of each foot[769]. Utilizing a process known as stereo photogrammetry SOLS algorithms produce a 3D image of the customer's feet and designs the insoles fitted to each individual.

US based company *Feetz* offers full 3D-printed customized shoes made of thermoplastic elastomers TPE, a rubbery material common in shoe soles. Initially, Feetz will cost between $200 and $300 a pair, though in is expected to halve that costs once the process is streamlined. A similar principal as Sols is pursued: the customer takes pictures with an app, can design the shoes individually and after ordering the system prints shoes that are tailored for each person's unique feet[770]. Along the same line the concept of *footprintfootwear* is following, a recently founded startup, that is utilizing 3D scanning, algorithm generative modelling and 3D-printing to create a unique pair of shoes fitting the individual customer. Starting with FDM they have come to SLS printing to achieve the best results for the materials and constructed structures. There is no product on the market yet[771].

For years designers have also taken advantage of 3D-printing possibilities when it comes to shoe designs. While some designs are only for fashion shows and must be seen as art objects, others can be downloaded from different internet platforms and printed out or ordered from printer hubs[772] .

[769] https://www.sols.com/
[770] http://www.feetz.com/
[771] http://www.footprintfootwear.com
[772] http://www.designboom.com/design/united-nude-3d-systems-re-inventing-shoes-milan-design-week-04-14-2015/
http://cubify.com/store/fashion/women (http://www.3dsystems.com)
http://www.tctmagazine.com/prsnlz/francis-bitonti-launches-mutatio-3d-printed-shoe-collection-united-nude/
http://www.tctmagazine.com/prsnlz/is-this-the-future-of-the-3d-printed-shoe/
http://www.continuumfashion.com/shoes.php
http://cargocollective.com/earlstewart/INFO-CONTACT

Designers have picked up on the idea of partly printing out soles and then combining them with other materials as leather (e.g. Designer *Earl Stewart* in New Zealand or adding decorative ornaments like designer *Katrien Herdewyn* Figure 132 and Figure 133).

For Dutch Design Week 2015 *Troy Nachtigall*, along with fashion designer *Pauline van Dongen* and industrial designer *Leonie Tenthof van Noorden*, constructed a shoe entirely from Filaflex – a filament material created by Spanish 3D-printing firm *Recreus* – the shoes took 100 hours in total to print, and are made up of a series of soft, vertical curving lines that move to increase flexibility. The shoes were manufactured by Dutch technology company SLEM[773] (see Figure 133).

Figure 132: Combination of 3D-printed sole with leather upper for shoes by Earl Stewart

Source: http://cargocollective.com/earlstewart/INFO-CONTACT

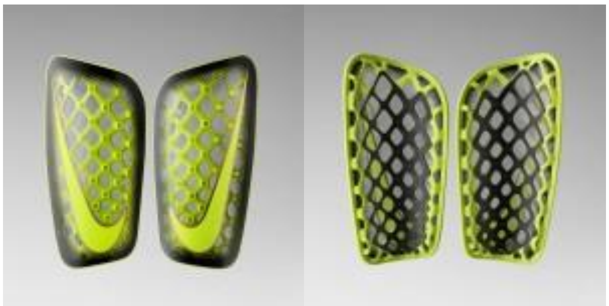
Figure 133: Examples of shoe designs (from top left to lower right: Alexander McQueen Alien Shoe; Continuum Strvct Shoes; 3D-printed heel in polyamide by designer Katrien Herdewyn, Filaflex shoe from Troy Nachtigall for Dutch Design Week 2015

Sources: http://www.vam.ac.uk/museumofsavagebeauty/mcq/alien-shoe/ http://www.continuumfashion.com/shoes.php https://i.materialise.com/blog/experimental-3d-printing-shoes-by-katrien-herdewyn http://www.dezeen.com/2015/10/20/troy-nachtigall-pauline-van-dongen-leonie-tenthof-van-noorden-3d-printed-high-heels-more-comfortable-than-normal-shoes/

[773] http://www.dezeen.com/2015/10/20/troy-nachtigall-pauline-van-dongen-leonie-tenthof-van-noorden-3d-printed-high-heels-more-comfortable-than-normal-shoes/

Customised textile production is important in the production of **protective clothing and sportswear**. Standard sportswear may be equipped with 3-printed knee protection, shoulder pads tailor-made on the basis of a body scan. *Nike* already applied 3D-printing for the design of shin protection, though at present not custom made. Protective wear for different types of sport is becoming an increasing issue to enhance safety of athletes, not only for American Football or ice hockey, but there is an increasing demand for protective wear in new fun sports, that are emerging.

Figure 134: 3D-printed shin protection by Nike



Source : *http://news.nike.com/news/nike-launches-summer-2014-football-equipment-innovations#/inline/30199*

Figure 135: Patent GB2490894 - Laser Sintered protective helmet liner and example for customised helmet for medical application

Sources: Patent GB2490894 - Laser Sintered protective helmet liner and *http://3dprint.com/97581/osteo3d-3d-printed-helmet*

The helmet liner shown in Figure 135 is stated to be Laser Sintered from DuraForm® Flex to provide it with a "rubber-like flexibility". Its 3-D lattice construction is an attempt to address the issue of poor air circulation which is said to plague conventional fabric liner designs. The patent also stated that silver could be added to the DuraForm® Flex powder mix prior to manufacture, thus allowing for the addition of anti-bacterial properties. However, inventions for security use, such as army or police forces, are covered by the confidentiality and cannot be disclosed in this study.[774]

In order to improve safety of bicycle helmets a project is led by *Cardiff University* using both powerful supercomputer algorithms and 3D-printed material, again applying Duraform® flex lattice structures[775]. The same principle is applied for football helmets within the same research group[776].

Another application area for protective clothing can be found in the sector of medical devices, where support structures can be printed out fitting the patient´s individual needs. In combination with padding textile materials they give the right support while providing the accuracy and comfort needed for some cases. In India a 3D-printed helmet supported the healing process of a 5 months old baby with cranisynostosis, where a helmet is needed to guide the proper healing as it puts pressure on indicated parts of the patient's skull, thus ensuring that bones are directed to expand properly just at the right spots (*Osteo3D*).[777]

Technical textile products also require specific fastening systems. Printing may offer a solution for small series and critical fastening systems. In this way, loops and hooks for anchoring can be integrated in textiles according to personal needs. In combination with electronic textiles this provides a vast field of application for emergency personnel, such as firemen, police or ambulance, as well as for leisure applications, like functional bike gear, mountaineering and other sports. Developments for military regarding protective clothing cannot be found through desk research and developers and researchers are subject to confidentiality, thus only projects that were publically available are mentioned in this study.

[774] Johnson A. et al. 2012, 2013 & 2014
[775] Soe, S. et al. 2014; http://3dprint.com/24386/3d-print-bike-helmet/
[776] http://3dprint.com/111461/3d-printed-protective-headgear/
[777] http://3dprint.com/97581/osteo3d-3d-printed-helmet/

3. Application area: Smart Textiles

The term "Smart Textiles" refers to a broad field of products that extend the functionality and usefulness of common fabrics. Thus a lot of definitions have been published, but smart textiles can overall be defined by their ability to sense stimuli from the environment and have the inherent capability to react and adapt to them by the integration of functionalities within the textile structure.[778] Electronic textiles describe the convergence of electronics and textiles into fabrics, which are able to sense, compute, communicate and actuate. As many different electronic systems can be connected to any clothing and various electronic components become smaller and smaller a wearable system becomes more versatile.[779] Wearable sensors must maintain their sensing capabilities under the demands of normal wear, which can impose severe mechanical deformation of the underlying garment/substrate. Current advances in textile technologies, new materials, nanotechnology and miniaturized electronics are making wearable systems more feasible but the final key factor for user acceptance of wearable devices is the fit comfort.[780] The pervasive features such as flexibility, low cost, robustness, unobtrusiveness, washability, small size, biocompatibility with human skin, and aesthetic sense are important requirements for the electronic textiles.[781]

Developments of electronic or smart textiles at present are mainly in Asia, but with quite a few research institutes and companies in Europe investigating electronic textiles. Examples of institutes are listed in Box 1.[782]

Box 51: Examples for research institutes and companies investigating Electronic or Smart Textiles

- Brunel University in Surrey (UK);
- Center for Micro-Bio Based Robotics of Instituto di Tecnologia (Italy)
- Dublin University (Ireland)
- Fraunhofer IZM (Germany)
- Fraunhofer IWS (Germany)
- Infineon (Germany)
- Insituto Italiano di Tecnologia – Center for Space Human Robotics (Italy)
- Patria (Finland)
- Philips research Laboratory (UK)
- Politecnico di torino, Politronica Inkjet Printing S.r.l. (Italy)
- Saxion University of Applied Sciences Enschede (The Netherlands)
- Tampere University of Technology (Finland)
- University Bolton (UK)
- University Ghent (The Netherlands)
- University of Southampton (UK)
- Wearable Technology Ltd. (based in UK, production in China)

So far systems include direct print onto textile materials in combination with traditional means of connection, like stitching of electronic devices onto textile material or weaving of conductive threats into fabrics. Most printing processes concentrate on one electronic component, such as printing of batteries or antennae, and combine the different elements by traditional methods with connecting wires or, on the other hand, stitch complex devices, such as batteries or sensors, onto textile material in combination of printing connections between them with conductive inks or pastes. Conductive materials, that are printable and stretchable, have been developed in order to meet demands of both conductivity and flexibility for electronic textiles.[783]

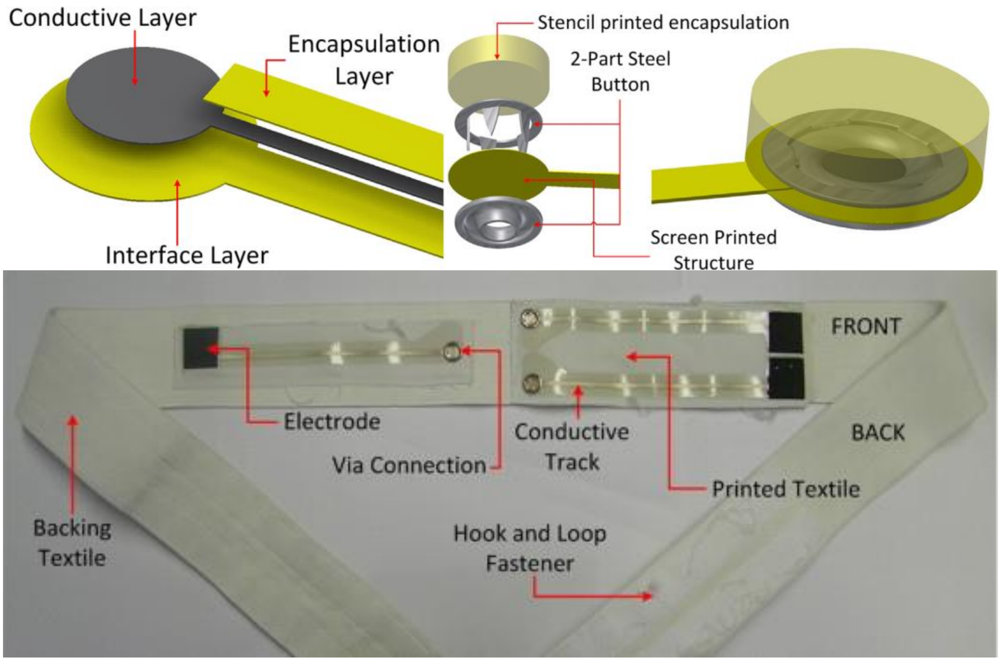
Two different approaches are observed in connection with 3D-printing: the use of conductive inks for direct print and the encapsulation of conductive wires or layers into insulating material. Conductive inks contain an appropriate highly conductive metal precursor such as Ag, Cu, and Au and a carrier vehicle.

Researchers from the University of Southampton have developed an innovative screen printed network of electrodes and associated conductive tracks on textiles for medical applications (Figure 136). A polyurethane paste is screen printed on to a woven textile to create a smooth, high surface energy interface layer and a silver paste is subsequently printed on top of this interface layer to provide a conductive track.[784] This technology can be amended by applying 3D-printing rather than screen or stencil printing, as is investigated by Saxion University of Applied Sciences. Silver pastes have been printed on to non-woven textiles to create wearable health monitoring devices. Developments of the Saxion University of Applied Sciences concentrate on printing conductive material onto textiles and connect them to electrically active patterns.[785] Key issues are the flexibility that is necessary for the textile surface, the bonding onto this surface and the maintenance of the functionality even after several washing cycles and during wear. Fraunhofer IWS uses dispenser printing, where a dispenser or extruder applies a pasty material onto a substrate via capillaries.

[778] e.g. Zhang and Tao 2001a, 2001b, 2001c
[779] e.g. http://www.wearable.technology/index.php/our-technologies
[780] Stoppa M & Chiolerio A., 2014
[781] Kim et al 2009
[782] Stoppa M & Chiolerio A., 2014
[783] e.g. Matsuhisa et al. 2014; Chun et atl. 2010.
[784] Gordon et al, 2014.
[785] Ir. Ger Brinks Saxion University of Applied Sciences Enschede, The Netherlands

The fabrication of a workpiece takes place in a computer-controlled manner according to pre-defined forms (CAD) and sizes. The applied material is dried or, depending on the material, sintered. Typical materials are metals, semi-conductors, polymers, ceramics and composites. The simultaneous application of several capillaries enables the generation of function-adapted components made from several materials. This results in bendable, flexible and conductive structures with a thickness of printed material of 20 to 30 µm.

Figure 136: An ECG chest band fabricated with screen and stencil printing



Source: Paul, G. et al, 2014

Applications for electronic textiles can be for medical applications, consumer products or various safety applications, such as:[786]

- Health monitoring of vital signs of the wearer such as heart rate, respiration rate, temperature, activity, and posture;
- Customized ortheses/prostheses;
- Sports training data acquisition;
- Monitoring personnel handling hazardous materials - Sensors integrated into clothing as part of personal safety applications;
- Tracking the position and status of soldiers in action;
- Monitoring pilot or truck driver fatigue;
- Textile RFID transponders for logistics or for anti-theft and anti-fraud protection in clothing;
- Large-area fabric with integrated sensors for alarm systems;
- Innovative Fashion (wearable technology);
- Textile keyboards or switches;
- Increasing safety through lighting and displays on and in fabric[787];
- Regain sensory perception that was previously lost by accident or birth.

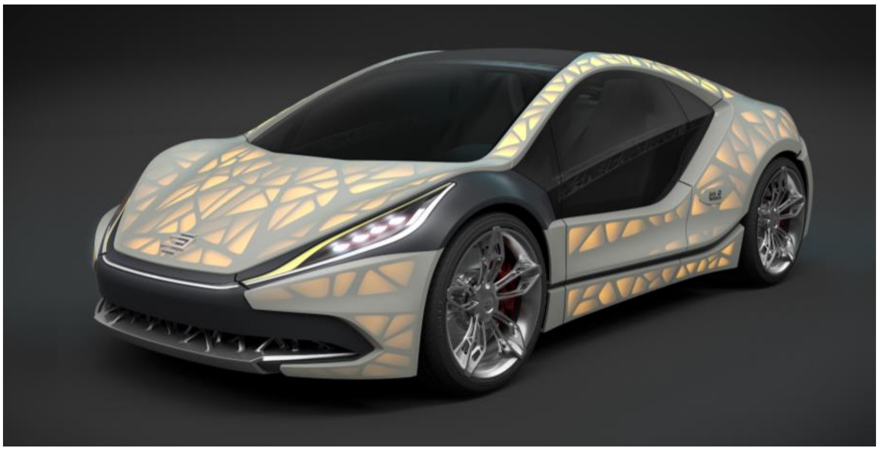
3D-printing entails opportunities for smart textiles. One of the possibilities is the encapsulation of smart textile devices. In combinations with 3D-printed conductive materials, it will open a market for directly printed smart three dimensional functionalities on textiles. So far other methods of application for electronic devices are used (stitching or screen, stencil or dispenser printing), but 3D-printing could open new possibilities. It has to be discussed, if printing of conductive cords with thickness used can be defined as being 3D-printed. For this reason the application area was described in the study for the sake of completeness and as it is a prospective application of the future. However, it will not be included in the following sections on supply chain and identified key players.

[786] http://www.fdm4tp.be/ or http://www.izm.fraunhofer.de/en/abteilungen/system_integrationinterconnectiontechnologies/arbeitsgebiete/elektronikintegrationinalternativematerialien/projects/integration_von_elektronikintextilien.html
[787] http://www.goose.london/2014/10/illum-jacket-illuminating-the-future-for-cycle-safety/

4. Application area: Light weight constructions

Textiles have been used for applications in light weight constructions as examples from automotive industry can demonstrate and shall be outlined very briefly here as a possible future application of textiles in combination with AM. EDAG has designed a car with a complete, bionically optimized vehicle structure, that was 3D-printed, combined with a weatherproof textile outer skin panel. *BMW* had introduced the idea of using textile material for car bodies in 2008.[788] "Combined with the topologically optimized, additively manufactured structure, it offers enormous potential and stimulus for the ultimate lightweight construction of the future" as EDAG CTO Jörg Ohlsen points out.[789] Constructions like this can find their way into the world of building & construction, mobility as well as consumer products.

Figure 137: "EDAG Light Cocoon": Combination of 3D-printed structure with textiles for light weight construction



Source: http://www.edag.de/

4.2.8.2 Identifying value chain components

(i) Identification of key players and usage of Additive Manufacturing

It has to be stressed again, that one has to distinguish between direct print on textiles and the combination of an independently 3D-printed piece with textiles by agglutinating or other bonding methods. 3D-printed "textiles" for purely designer applications and the agglutination of 3D-printed parts onto textile materials is on a different level of development and already close to (mass) production for consumers.

Concerning the 3DP equipment providers (software and hardware) well-known companies such as 3D Systems, Stratasys in the US or European companies like EOS or Materialise are key players in the textile sector as well. On the side of material development there are also some new and specific companies such as *Recreus* (Spain) or Plastics2print and Colorfabb (The Netherlands) that are developing and offering specific technologies for producing textiles and shoes and new material combinations. The UK-based Tamicare is another player emerging in the field that is producing textiles from cellulose, aiming at sanitary products and possibly medical applications.

Direct 3D-printing on textiles to add functional parts on the other side is not that far developed and results mostly in research prototypes. A lot of research is going on within Europe (see list of interview partners and key players in section 4) to build up knowledge of combination of different parameters, such as printing conditions or materials, that can be combined, while at the same time the development of new materials and 3D-printers is progressing fast.

Application of AM can be found in the section of customized protective clothing, for medical applications on one side and tailor-made sports or military equipment. As developments for the latter are mostly subject to confidentiality only very few examples could be found. A patent by *BAE Systems* (UK) relating to the Additive Manufacture of a liner for a ballistic resistant helmet shall be cited here as an example for application of 3D-printing for protective clothing. Also the Finnish company Patria is developing military equipment and involved in projects mainly relating to electronic and smart textiles.

Medical applications such as ortheses or support structures fitting the patient´s individual needs are another sector of interest, but were not further followed in this case study.

788 https://www.youtube.com/watch?v=IGf3pzOydd0

789 http://www.edag.de/en/edag/news-detail/getarticle/News/detail/edag-light-cocoon-the-ultimate-in-lightweight-construction.html

Regarding sports equipment products by Adidas, Nike or New Balance have already been explained in Section 4.2.8.1(ii)2. Not only personalized and tailor-made sport shoes is a potential market for integrating 3D-printing into shoe manufacturing process, this technology has the potential to shorten the supply chain by combining labour-intensive production steps.[790]

Nike debuted first in 2013 with the first-ever football cleat built using 3D-printing technology, with Adidas and New Balance following in 2015 with midsoles printed of elastomeric material. All companies use SLS technology for printing, the elastomeric material came from 3DSystems, Adidas working in partnership with European firm Materialise. The (mid)sole is printed out in one piece with special design, thus being able to fit the stiffness of the sole to the special needs of an athlete. The future will be that soles with individual cushioning elements can be designed to each runner based on underfoot pressure data. Also for other sports, like football, special designs fitting each athlete, can be created, soles printed out individually and fixed to upper parts. Nike's COO Eric Sprunk spoke about customers in the future walking into a Nike store and having a 3D-printed shoe made in a matter of hours.[791]

(ii) Composition of the value chain

The value chain for the various textile applications varies in relation to the specific application field, though, on an abstract level it could be generalised as illustrated below. However, when describing the various players in the value chain we focus on the application in the area of textile printing and design as well as shoes and protective clothing (as presented above in chapter 1.2 and 1.3.).

The 3DP hardware and software producers are one important element of the value chain and are relevant in any sub application case. In addition, designers and other service providers have an important role in the value chains which offer consumer products (not smart textiles and technical textiles). ***Designer*** such as ***Jiri Evenhuis*** from the Netherlands and designers, that offer their developments in open source networks, are important promotors for the use of 3DP for trendy wearable textiles.

In general, all applications in the textile sector as analysed in this case study are still in development stage or just in the market introduction stage, currently they address very specific and rather narrow high-end markets. Only niche and designer products are on the market and can be printed at home, while mass production of textiles or textiles in combination with 3D-printed parts still awaits the successful implementation in the production process.

Probably, the most well-known case is the shoe case (Adidas etc.) and its value chain. Adidas is located in Germany and will use various well-known 3D equipment providers. Personalization is a key trend in show design and we will see more applications in the future. However, due to the fact that the products are just before market entry we cannot identify any established value chain.

Original Equipment Manufacturers (OEMs). For the use in textile applications Fused Deposition Modelling (FDM) is the most commonly used printing technology as it is an inexpensive method and furthest developed for private use or small companies. A lot of cooperation is with big companies like ***Materialise***, ***cubify*** (now 3D Systems) or ***Stratasys***, but a lot of research institutes are using open source devices, that are specifically compiled and adapted by small companies for their need. Small FDM printers, as can be obtained from cubify for example, are used for customer applications, such as printing out accessories or the like. Home desktop printers are offered from various companies worldwide, with a strong market in US and China, but also a lot of upcoming companies in Europe (see list in Annex 13).

Main obstacle for textile industry to use 3D-printing is the fact, that this technology is not yet available for in-line processes. The breakthrough is expected if this obstacle is overcome and in-line processes make direct 3D-printing on textiles possible. However, at present 3D-printing seems to have a breakthrough in shoe industry, as shoe technologies continue to evolve the number of shoe pieces added together has increased, requiring increasingly complicated manufacturing steps to produce shoes. 3D-printing can help to shorten some steps in the production process. Here SLS technology is used for producing shoe parts, like mid or insoles, as different materials can be processed resulting in products with more suitable features. This process is not an in-line process yet, but as shoe production has various process steps, this is not so much an obstacle as it would be for mass production of clothes.

Provision of raw material. Materials used for 3D-printing in connection with textile applications range from elastomeric materials to rigid or conductive materials, depending on the intended use of the printed parts and on the printing technology used. A lot of small start-up companies in the US and Europe, especially the Netherlands, are developing new materials that are available over the internet. However, these companies are far from being profitable yet. New business models have to be considered to help that these companies become established on the market.

[790] http://fortune.com/2015/12/15/3d-printed-shoe-race/

[791] http://news.nike.com/news/nike-debuts-first-ever-football-cleat-built-using-3d-printing-technology

Examples for such small business companies or inventors are ***Colorfabb***; ***CC-Products***; ***plastics2print***; or ***Recreus***[792], a more comprehensive list of suppliers, if not inventors is given on the ***RepRap*** homepage[793].

When it comes to **printing of textile material** UK based company ***Tamicare*** is the only outstanding producers. Tamicare is understood to be in talks with a large US company that could sell the women's undergarments in the USA. Cosyflex is also reported to be gaining interest in the medical devices market as a compression bandage, with a UK company possibly looking to commercialize products.

(Software) Design. A lot of **designers** are using either 3D-printed elements as accessories or print whole items[794]. The most prominent designer of 3D-printed fashion is ***Iris van Herpen***, with others following en suite. These printed fashion garments have to be considered as art for fashion shows, but not suitable for daily wear yet. For shoe design a lot of designers have picked up on the idea of either partly printing out soles and then combining them with other materials as leather or directly printing out customized shoes. Examples for these designers are ***Earl Stewart*** (New Zealand), ***Katrien Herdewyn, Troy Nachtigall, Pauline van Dongen*** & ***Leonie Tenthof van Noorden***.

A lot of accessories are offered on the internet, where data can be downloaded for home-printing (e.g. ***cubify*** (now 3D Systems), ***shapeways***, ***aoku***, ***thingyverse***, ***mgxbymaterialise***[795]), starting from jewellery to handbags or hats and decorative patterns, that are printed on textile nets and can be stitched onto garments.

Industrial applications. While 3D-printers are already used in several fields by companies and individuals, printing of textile-like patterns is still rare. In technical textiles, 3D-printing has already been used to create applications such as flexible heating systems or wearable technology. In design, garments such as bikinis, complete dresses or shoes are 3D-printed. These garments, however, are clearly produced for show, not for everyday wearing.[796] Applications focus on the combination of 3D-printed elements with textiles, e.g. as for shoes, where the sole is printed and then fixed to the upper part, making it difficult to identify key players within other sectors of the textile industry.

Personalization is the upcoming trend in shoe design and printing of individual parts not only for protective clothing but also for everyday clothing. Some start-ups in the US are already offering 3D-printed in-soles or customized 3D-printed shoes (e.g. ***Feetz, Sols***, ***footprintfootwear***) utilizing 3D scanning and algorithm generative modelling. Big sports companies as ***Nike***, ***Adidas*** and ***New Balance*** have already started to work with 3D-printing technologies and have advertised their 3D-printed shoes, protective wear or accessories.

In regard to application of 3D-printing in combination with textiles the ***customer*** him/herself is becoming a strong key player, providing own services and designs to other users. Additionally to their online shops also Materialise and others have established global networks of local distributors and resellers of their design collections.

Research and Technology Organisation. New technologies and combination of printing materials, as well as input from other printing techniques, such as ink-jet printing, help to develop new applications thus leading to new and fast developments of 3D-printing technologies. The use of recycled materials, such as cellulose fibres, is in focus of research institutes across Europe, such as ***Saxion*** or ***VTT***, but these materials cannot be printed directly yet as solvents for fibres need to be evaporated rapidly in order to make direct printing possible. Recycling and sustainability are the strongest arguments for 3D-printing as production can be achieved without too many remnants and waste. Also recycled and biodegradable plastic material is available, making it possible to find material for various applications. Key issue for 3D-printing in connection with textile remains the bonding between the textile and the printed item, either through agglutination or direct printing on textile surfaces. Here a lot of research is conducted in European research institutions, as it is the knowledge on possible material combinations and printing conditions that can make European industry leading in the section of textile processing (e.g. ***Sächsisches Textilforschungsinsitut STFI*** (DE), ***Textilforschung Thüringen*** (DE), ***Centexbel*** (BE), ***Saxion*** (NL), ***Fraunhofer Insitutes*** (DE) and others.

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792 http://colorfabb.com/
Inventors like http://cc-products.de/ products are available through https://www.matterhackers.com/store/3d-printer-filament/poro-lay-lay-fomm-filament-175mm
http://www.plastic2print.com/
http://recreus.com/en/

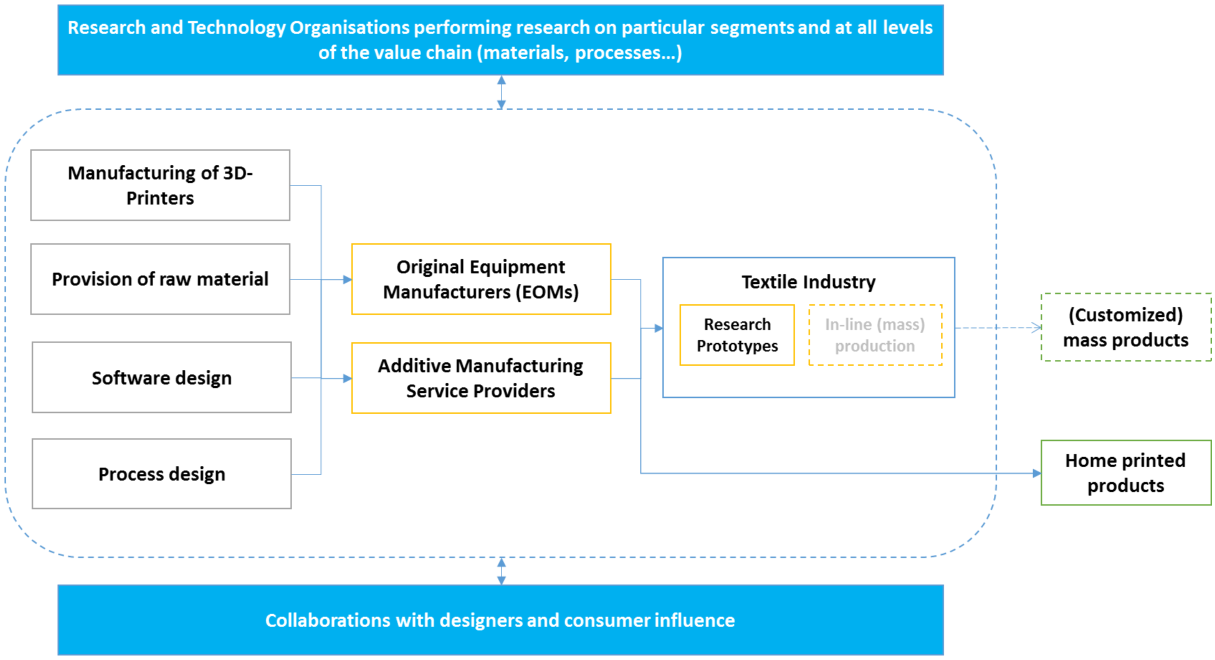
793 http://reprap.org/wiki/Printing_Material_Suppliers or http://3dplatform.com/top-10-new-3d-printing-materials-you-should-try-part-i/

794 http://www.jannekyttanen.com/
http://www.irisvanherpen.com/haute-couture
http://hinzepia.wix.com/muted
http://www.noaraviv.com/hard-copy-collection/5mgbebz32pkiokkc2wjntwzce6ku72

795 http://www.shapeways.com/
https://www.aoku3d.com/
https://www.thingiverse.com/
https://mgxbymaterialise.com/

796 see Melnikova, R. et al., (2014). Input also from Interviews with Ger Brinks, Karen Deleersnyder, Sarah Göbel and Frank Siegel.

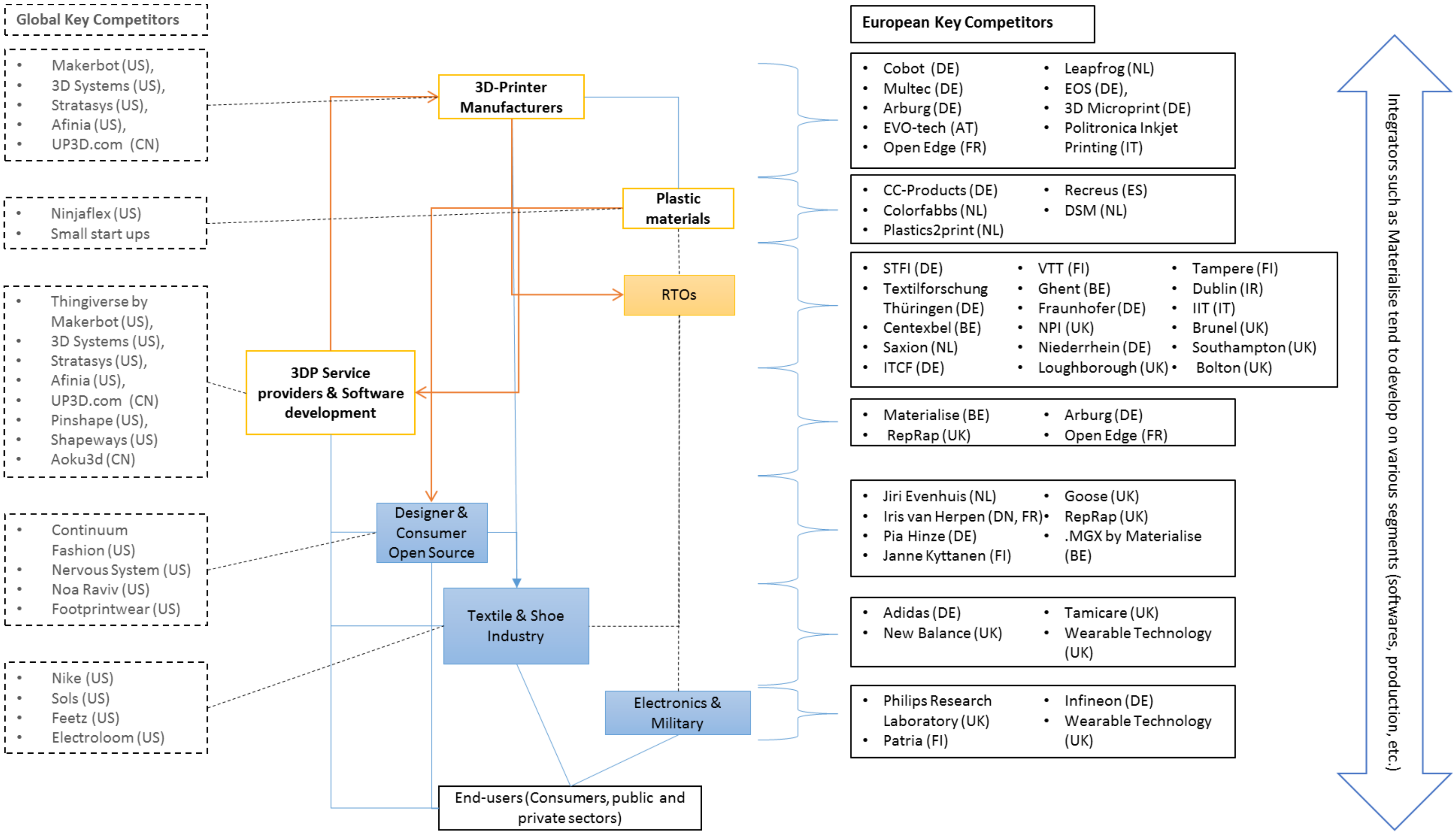
Figure 138: Main segments of the value chain of 3D-printing & Textiles



Source: Own depiction

The figure below shows more specifically some important European and Non-European players in the textiles value chain in Europe. At the moment, we cannot identify any key region or cluster where 3DP applications related relationships are of significant importance. However, European research institutes play a strong role in development of knowhow concerning 3D-printing on textiles and development of electronic textiles, where Asian research has also a strong impact.

Figure 139: Illustration of the textile related additive manufacturing value chain



Source: Own depiction

(iii) Functioning of the value chain and critical factors

3D-printing in context with textiles has already been used to create applications for smart textiles, such as flexible heating or wearable technology. Textile materials printed out are used merely for design, such as bikinis, dresses or shoes, which are produced clearly for show not for everyday wear. Applications focus on combination of 3D-printed items with textile materials, for example for midsoles or insoles for shoes or protective parts for protective clothes.

Another benefit of 3D-printed textile garments, like CosiflexTM by UK based company TamicareTM, is the reduction or complete shortfall of clippings and waste material. Also customized items increase customer satisfaction as garments or shoes fit exactly the anatomy of each individual again resulting in products that are not given away because of misfit or pressure marks.

At present small companies develop new innovative materials, but they are far away from being profitable. Materials used must be suitable for FDM, but also new developments for sintering could be interesting in combination with textile material. Of great interest are recycled materials or biodegradable materials, as well as materials with different functions, such as conductibility or flexibility. Crucial point in functional textiles, combining 3D-printing with textiles, is the adhesion of the printed material to the textile. A lot of know-how on combination of different materials and printing techniques is built up in Europe in various research institutes, some of them are listed as interview partners below. Ideas for new developments can be based on experiences from ink jet printing or screen printing.

Applications for textile industry, where 3D-printing is of greatest benefit, will lie within consumer products, such as individualized clothes, but also within protective clothing and functionalized clothing. Support materials either for orthodontics or protective wear as well as insoles for shoes, which are already in development or are said to come on the market shortly. Customized shoes are envisaged by big players in the sports industry, taking into account not only anatomy of each individual but also different underfoot pressure, in order to design the optimal (athletic) shoes. For printing midsoles and insoles mostly laser sintering is used in combination with an elastomeric material and special design, but there are further developments of new materials from start-up companies, typically situated in the US.

Use of 3D-printing to produce smart textiles is another possible application area for the future. Electronic textiles are able to sense, compute, communicate and actuate, but must maintain their sensing capabilities under the demands of normal wear, which can impose severe mechanical deformation of the underlying garment/substrate. Current advances in textile technologies, new materials, nanotechnology and miniaturized electronics are making wearable systems more feasible but the final key factor for user acceptance of wearable devices is the fit comfort, robustness, unobtrusiveness, washability, small size, biocompatibility with human skin, and aesthetic sense.

3D-printing entails opportunities for smart textiles for e.g. medical applications, consumer products or various safety applications. In combinations with 3D-printed conductive materials, it will open a market for directly printed smart three dimensional functionalities on textiles. So far other methods of application for electronic devices are used (stitching or screen, stencil or dispenser printing), but 3D-printing could open new possibilities.

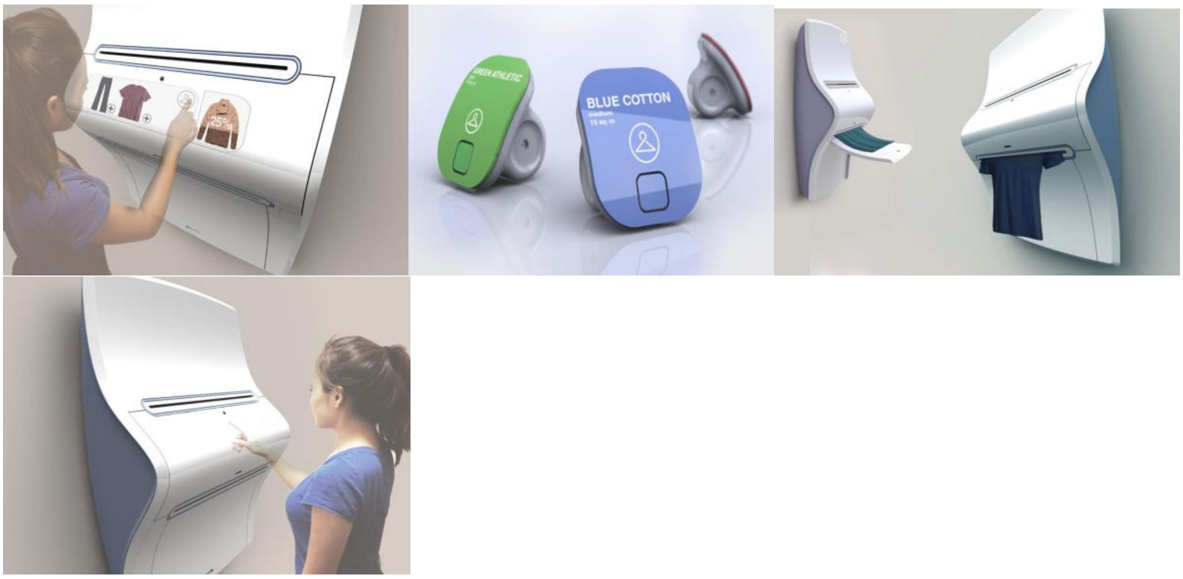
Futuristic ideas for the future of textiles in combination with 3D-printing come from designers and research companies. Designer Joshua Harris imagined the future of textile printing by envisioning a textile printer for the Electrolux Lab design competition in 2010, that also recycles used textiles back into thread and stores it in the respective cartridges (Figure 140).

A self-repairing 3D-printed shoe from protocells is another futuristic project from UK designer Shamees Aden working scientist Dr Martin Hanczyc from the University of Southern Denmark[797]. The Amoeba surface-adapting trainer is a conceptual prototype for 2050 that seeks to probe the future of new materials derived from Protocells. The study of protocells is a new and emerging science that has the potential to drastically revolutionise the way we make materials. Essentially protocells blur the gap between the non-living and the living. Engineering the emergence of life from lifeless liquid chemicals manufactured artificially in the laboratory could provide the building blocks to create a new-made nature.

In order to support start-ups within this value chain user-oriented initiatives with open source character should be promoted (such as e.g. Fab Labs or 3D Hubs, as described in the previous application field).

[797] http://shameesaden.com/AMOEBA-TRAINER

Figure 140: designer Joshua Harris' view on textile printing in the future



Source: http://inhabitat.com/joshua-harris-3d-clothing-printer-recycles-old-garments-to-create-new-apparel/

4.2.8.3 Missing capabilities

(i) Regional Dimension and missing capabilities

Looking at the regional dimension of the case study we can observe that the value chain and relationships between the various players are just emerging. At the moment, we cannot identify any key region or cluster where 3DP applications related relationships are of significant importance. However, European research institutes play a strong role in development of knowhow concerning 3D-printing on textiles and development of electronic textiles, where Asian research has also a strong impact.

Some established but also a number of new companies in the UK, Belgium, the Netherlands and Germany might become key players in the field. Design objects of 3Dprinted (textile) structures are produced rather for show than for everyday wearing, but a strong designer community has established mostly in Denmark, the UK and the Netherlands. Designer offering their developments in open source networks are important promotors for the use of 3DP for trendy wearable textiles.

By and large 3DP applications in the textile industry are just emerging and are at present mainly in the development and prototyping stage. A key "missing capability" is hence the lack of technological knowledge about how to industrialise 3D-printing technologies integrating 3D-printing in very fast in-line processes of the textile industry. Concerning research in the field of application of 3D-printing on textiles we have identified many European players as quite active. Research institutes in Belgium, the Netherlands, the UK, and Germany are most outstanding, for research in electronic textiles also in Italy. As 3D-printing also entails opportunities for smart textiles for e.g. medical applications, consumer products or various safety applications. In combinations with 3D-printed conductive materials, it will open a market for directly printed smart three dimensional functionalities on textiles. Companies with products close to the market or already on the market come from the UK, Germany or Finland.

Concerning the 3DP equipment providers (software and hardware) well-known companies such as 3D Systems, Stratasys or EOS are key players in the textile sector as well. However, there are also some new, small and innovative companies such as Recreus (Spain) or Plastics2print (The Netherlands) that are developing and offering specific technologies or material for producing textiles and shoes and new material combinations. The UK-based Tamicare is another player emerging in the field that is producing textiles from cellulose, however, the products are not available in shops yet.

Furthest developed is the application of 3D-printed soles for athletic shoes, with Adidas in Germany and New Balance in the UK cooperating with Materials from Belgium or US designers, printing material used comes from US company 3D Systems. Apart from applications for shoes and some niche (designer) products 3Dprinting of textiles and on textiles result mostly in research prototypes at present.

In order to promote applications in this field collaborations within the value chain should be supported. Especially collaborations between research institutes and textile industry, and also with 3D-printing end users, including 3D-printing communities.

Regarding Eastern Europe no relevant key players in the value chain of 3D-printing of textile consumer products could be identified.

There is a need to increase understanding of new reliable materials including better simulation and software, particularly software that allows the simulation of how the product will react after curing or melting with different materials. A more common baseline for comparability in tests between different materials and machines is also necessary.

A focus must be laid on the ***industrialisation of 3D-printing technologies***, for instance the development of new production systems with linked 3D-Printing and traditional technologies and data systems/interfaces to achieve highly integrated and combined technologies. Crucial point to bring 3D-printing into textile industry will be the achievement of in-line printing of functional parts on textile material, in order to make processes more productive. In combination with principles like Cyber-Physical Systems and the Internet of Things personalized production may become reality even for textile industry, printing functional, individual elements on textiles or combining 3D-printed parts like soles with textile elements to create customized items. Customization of plastic parts produced by injection moulding or thermoforming always requires adaptations to the production process (such as the production of specific moulds) Small series will become economically more efficient if the basic piece may be produced conventionally in larger series and the individual objects customized by means of 3D-printing to the wishes of the client. It may also be economically interesting that the 3D-printed material is different from the basic material to obtain a complementarity in the material properties.[798]

(ii) Barriers to the uptake and further deployment of AM in the value chain

Although the development of AM along this value chain is currently strongly driven by designers, IPR do not appear to be a barrier to AM diffusion. Their designs are indeed usually protected. Some designs are available on open source platforms. Research organisations are building up knowledge within their research projects, which are either confidential or regulated in (bilateral) contracts. Some other barriers could however be identified which are presented below.

Value chain-specific dynamics

- **Common research efforts between players** could possibly support and accelerate R&D processes.
- **Only little interactions between players** in this application area were identified. In order to promote applications in this field collaborations within the value chain should be supported. Especially collaborations between research institutes and textile industry, and also with 3D-printing end users, including 3D-printing communities.
- **Concentration of key players in Western and Central Europe.**

Knowledge

- Due to the hype in 3D-printing public see high quality 3D-printed finished parts made with expensive high-end printer. The assumption is that these objects can be created with machines of lower quality and costs and without training. However, the modelling process is a time and labour consuming process, learning 3D modelling, 3D scanning and editing of the scan data. Downloading 3D models very easy from bureaus but creating and modifying correctly is not easy.
- As mentioned above there is a need to increase understanding of new reliable materials including better simulation and software, particularly software that allows the simulation of how the product will react after curing or melting with different materials. A more common baseline for comparability in tests between different materials and machines is also necessary.

Technology performance

- **R&D and innovations** are needed in the area of textile production with AM technologies.
- **Current technological performance is problematic** as it does not yet match the existing production technologies. A focus must be laid on the industrialisation of 3D-printing technologies, for instance the development of new production systems with linked 3D-Printing and traditional technologies and data systems/interfaces to achieve highly integrated and combined technologies. Crucial point to bring 3D-printing into textile industry will be the achievement of in-line printing of functional parts on textile material, in order to make processes more productive. In combination with principles like Cyber-Physical Systems and the Internet of Things personalized production may become reality even for textile industry, printing functional, individual elements on textiles or combining 3D-printed parts like soles with textile elements to create customized items.
- The **size of the build element** is dependent on each machine and the 3D-printing technology being utilised.
- **Long process times** are commonplace. These are typically apparent when using laser-based processes for the manufacture of large components. Process times can be increased by making the layers thicker, resulting in poorer surface finish quality. Developments in laser technology address this issue.

[798] http://www.fdm4tp.be/

- **Costs** compared to conventionally produced textiles as costs of parts are based on material used, so big objects are expensive. The raw materials used in 3D-print are also much more expensive than material used traditional manufacture, prices range from £20 to £300 per kg.

Missing capabilities: materials and finishing

The second phase of case study research led to a better delineation of possible missing capabilities. It was confirmed that specific capabilities were missing which are currently hampering the uptake and deployment of AM. **Appropriate capabilities in the field of AM materials are missing:**

- Materials used for 3D-printing in connection with textile applications range from elastomeric materials to rigid or conductive materials, depending on the intended use of the printed parts and on the printing technology used. A lot of small start-up companies in the US and Europe, especially the Netherlands, are developing new materials that are available over the internet. However, these companies are far from being profitable yet. **New business models** have to be considered to help that these companies become established on the market.
- Engineering **grade material selection** is limited in comparison to conventional manufacturing processes. This issue continues to be addressed with the evolution and development of new materials.
- **3D-printed parts are not as strong** as traditionally-manufactured parts. Injection moulding for example provides an even strength across the part, as the material is of a relatively consistent material structure. Development and testing of materials for higher performing materials with additional isotropic properties, increased stiffness's and strength, and creep behaviour needs to be encouraged and supported by funding.
- Uncontrolled **surface roughness** and undesirable stepping on curved surfaces due to the inherent additive building methodology may inhibit built quality. The printed models are usually a matt finish with rough layer lines. 'smooth' surface finish requires post-processing generally involves labour and/or chemicals, resulting loses of detail and tolerance on parts
- **Resolution** of 3D-printed parts: Need for **sufficient distances between structures** to create woven or knitted-like structures.

4.2.8.4 Conclusion: opportunities for public support

The value chain for the textile applications varies in relation to the specific application field. We focussed on textile printing and design as well as shoes and protective clothing. 3DP hardware and software producers are one important element of the value chain and are relevant in any sub application case. In addition, designers and other service providers have an important role in the value chains which offer consumer products. Designers offering their developments in open source networks, are important promotors for the use of 3DP for trendy wearable textiles. In general, nearly all analysed applications in the textile sector are still in development stage or just in the market introduction stage, currently they address very specific and rather narrow high-end markets. Only niche and designer products are on the market and can be printed at home, while mass production of textiles or textiles in combination with 3D-printed parts still awaits the successful implementation in the production process. Probably, the most well-known case is the shoe case (Adidas etc.) and its value chain. Personalization is a key trend in show design and we will see more applications in the future.

In regard to application of 3D-printing in combination with textiles the customer him/herself is becoming a strong key player, providing own services and designs to other users. Additionally to their online shops also Materialise and others have established global networks of local distributors and resellers of their design collections. Personalization is the upcoming trend in shoe design and printing of individual parts not only for protective clothing but also for everyday clothing. Some start-ups in the US are already offering 3D-printed in-soles or customized 3D-printed shoes (e.g. Feetz, Sols, footprintfootwear) utilizing 3D scanning and algorithm generative modelling. Big sports companies as Nike, Adidas and New Balance have already started to work with 3D-printing technologies and have advertised their 3D-printed shoes, protective wear or accessories.

Based on the previous chapters we give some policy recommendations:

1. Main obstacle for textile industry to use 3D-printing is the fact, that this technology is not yet available for in-line processes and hence more R&D is needed. The breakthrough is expected if this obstacle is overcome and in-line processes make direct 3D-printing on textiles possible. However, at present 3D-printing seems to have a breakthrough in shoe industry, as shoe technologies continue to evolve the number of shoe pieces added together has increased, requiring increasingly complicated manufacturing steps to produce shoes. 3D-printing can help to shorten some steps in the production process.
2. New technologies and combination of printing materials, as well as input from other printing techniques, such as ink-jet printing, help to develop new applications thus leading to new and fast developments of 3D-printing technologies. The use of recycled materials, such as cellulose fibres, is in focus of research institutes across Europe. Recycling and sustainability are the strongest arguments for 3D-printing as production can be achieved without too many remnants and waste. Also recycled and biodegradable plastic material is available, making it possible to find material for various applications. Key issue for 3D-printing in connection with textile remains the bonding between the textile and the printed item, either through agglutination or direct printing on textile surfaces.

Here a lot of research is conducted in European research institutions, as it is the knowledge on possible material combinations and printing conditions that can make European industry leading in the section of textile processing. Accordingly, this type R&D has to be further strengenthend and supported, also by the European Commission. The technical limitations of AM and missing knowledge imply that further **R&D** is conducted with relevant **co-investment from the public sector** (at regional, national and EU levels) for areas such as:

   a. AM processes, esp. resolution of 3D-printed parts
   b. Materials selection, materials properties including health impacts (esp. also recycled materials, such as cellulose fibres);
   c. Quality monitoring, control and detection systems;
   d. High-performance and high-volume production;
   e. Printing cost reduction.

3. Consequently, collaborations should be supported, especially between research institutes and textile industry. In order to promote applications in this field collaborations within the value chain should be supported. Especially collaborations between research institutes and textile industry, and also with 3D-printing end users, including 3D-printing communities. In addition, opportunities emrge in suing textiles in other industries such as automotive and aircrafts, hence there are cross-sectoral collaboration opportunities. Electronic textiles offere a huge opportunity as well, however, these appllications where not in focus of the case study on specific value chains.
4. The development of new business models should be supported. This is escpecially relevant for the alreaedy further advanced applications in the shoe and protective clothing area where the specifics of the individualisations can alreadxy be exploited and adresses specific customer needs.
5. Activities supporting the involvement of users should have an open source character. In co-operations with research organisations clear contracts have to be signed to protect knowledge advantages from research in Europe. Support and supply of information for small enterprises regarding the protection possibilities for their designs. Support for SMEs in case of harm of their IPR would in that sense be interesting.
6. New curricula (regional and national levels are here concerned but the EC could still take a coordination role here) should be developed in order to foster the diffusion of relevant skills among the EU workforce;
7. Finally, platforms and networks for consumer participation should be strengthened a strong driver for the development are users which can pull the development and form a critical mass which finally could facilitate the formation of larger markets.

4.2.9 Affordable houses

4.2.9.1 Scoping

(i) Context

Only very recently construction 3D-printing has begun to move from an architect’s modelling tool to delivering full-scale architectural components and individual elements of buildings, e.g., walls and facades (Lim et al. 2012). According to Bassoli et al., (2007), ‘The techniques based on layer-by-layer manufacturing are extending their fields of application, from the building of aesthetic and functional prototypes to the production of tools and moulds for technological prototypes or preseries’. Specifically, large-scale 3D-printing, such as ‘mega-techniques’, is becoming more and more relevant especially since 29 March 2014 when work began on the world’s first 3D-printing house (Wainwright 2014). However, Perkins & Skitmore underline (2015) it not clear which role 3D-printing currently plays in the construction industry and where this technique could be heading towards the future. Although several AM technologies have been around for up to 20 years, the new thing is the scale up of valorisation activities, many driven by the competition between Europe, USA and Asia (see).

Figure 141: Illustrative applications of 3DP houses from the Chinese player Winsun

Source: http://factor-tech.com/3d-printing/3421-are-3d-printed-houses-practical-the-experts-weigh-in/

Experts see that 3DP in construction is currently at an early stage of development and that activities are still mainly concentrated at the level of research and prototyping of components. It is estimated that a real market for 3DP in construction will only appear in 5 to 10 years (Interviews Bier and Jähne). Here one limitation is the conservative nature of the construction sector and its overall reluctance to innovate. The construction sector often consists out of many smaller suppliers and overall R&D budgets are nothing compared to those in automotive or aerospace. This does not benefit industrial renewal (Interview Francis). Another challenge is that the construction of houses is based on components that require multi-performative and multi-mode operations which implies a much more complex setting than for example the automotive industry. This means that a combination of new techniques is needed, and this goes well beyond additive manufacturing alone. Researchers are currently still working on figuring out which techniques are efficient enough to use for which components. Once this understanding is maturing a tipping point maybe reached and the creation of markets can get fueled via more active industry involvement (Interview Bier).

There is indeed a trend towards a holistic view to buildings. The implementation of such a view will need 3D-printing for certain parts of the building but also other techniques (such as subtractive techniques) and operations (such as robotics). In fact, it are the researchers and architects that see the role of 3DP for the construction sector in a broader sense than the vast majority of the construction sector itself. In general they talk about the role of digitalisation (digital fabrication) for the transformation of the construction sector. This view contrasts with an overall very traditional construction sector that lags behind and is characterised by a low productivity. Indeed, 3DP and other assembling techniques make use of digitalisation and question current building technologies. The challenge is to merge these multiple players, cultures, and industries together as to be able to come up with more efficient, faster and less costly production of components and buildings. The advantage of 3DP to society and industry is that it could reduce costs, cut waste and slash the carbon footprint of the construction sector (Sköld and Vidarsson 2015).

Box 52: The importance of customisation for the construction sector

Another key trend is the fact that online applications will appear where clients can customize their houses. New business model could appear where people can order new doors or new colors for their house even by paying monthly fees or membership money (e.g. Spotify). For example if you get a new baby you could order a fully new room. Own design is becoming important.[799]

A third key trend is that in the European economic downturn some construction companies driven by the search for value added started to realize more intensely that they will be forced to innovate if they want to keep the lead. As cost-cutting rounds are not sufficient anymore to stay in the game new initiatives resulted that mainly consisted out of a valorisation of existing AM technologies for construction (Interview Salet). A last key trend is that engineering consultancy companies, one key player in the value chain, have started to pick up the use of digital design with practices such as parametric design and optimization (Interview Jähne).

[799] Source : Interview Krug.

(ii) Application area: Affordable houses

During the first phase of the study, the area entitled "Construction sector / building technologies, affordable houses based on automatization, redundancy of formworks" was selected. At this stage we would like to stress the early developments of AM applications in the field of construction what implies that no mature applications exist yet and value chain and markets are still to be established. Nevertheless, the choice to include this application area was based on its potential high positive impact on the reduction of green gases due to more efficient production techniques implying a productivity rise for the entire construction industry. The construction sector is one of the corner stones of modern economies and therefore should be followed up closely when it comes to new trends potentially leading to big changes as in the case of digital fabrication and more specifically AM. Furthermore the construction sector has a broader outreach potential to other sectors such as aerospace, defense and offshore. AM is associated both to functional and non-functional parts and especially to the design.

Based on a review of sources we identified four broad potential application areas where AM can cross-fertilize the construction sector[800]: (1) Design application and structural Engineering advices such as the familiar models use by architects to illustrate their design; (2) Material related advices and supports such as the structural engineers of the global design and engineering consultancy ARUP looking at AM to optimize construction steelwork applications in a variety of complex buildings; (3) Mechanical equipment related advices and supports; (4) Construction manufacturing. At this early stage of AM development in the construction sector the approach selected in this case study is to emphasize the development of products for which experts have expressed a high probability for future markets to develop. Both from the desk research and interviews (interviews Bier and Jähne), it became clear that one central challenge for AM in construction manufacturing is to produce bigger components that should be integrated and assembled. Based on that evidence the application area under investigation will be **affordable houses**. Indeed, AM is currently being tested to manufacture future 3DP houses and temporary buildings (like pavilions for festivals that only stand for a few days/weeks - or shelter in disaster areas), custom made interiors or building details. Different materials and AM technologies are being used to make entire buildings, building components or furnishings for buildings. Here the use of AM renders constructions more sustainable, less expensive, stronger, smarter, recyclable, and customizable to the environment.

Box 53: The Minibuilders project as an example of how new concepts could disrupt the construction sector (IAAC, Barcelona)

"Within the construction industry we haven't seen any disruptive technologies being introduced for almost a century," stated the IAAC research team. "We believe that robotics and additive manufacturing will play a key role in the construction industry of the future." The Minibuilder lineup consists of three different robotic devices (foundation robot, grip robot, vacuum robot), each with dimensions no larger than 42cm. Despite their small size, they are capable of printing buildings of almost any proportion. All three robots, all responsible for different functions, are required during any large 3D-printing project. Working together these Minibuilders are able to produce large scale 3D-prints without the need for a large scale 3D-printer. Although the technology may not have been perfected, researchers have put in place a stepping stone for a new method of printing buildings and other large object, which we are sure will continue to develop[801].

One has to distinguish between three techniques based on the size of the object used. The traditional 3DP is used for smaller objects (parts are smaller than printers). But printing entire buildings requires new AM solutions. One key solution offered is the use of very large printers that do either produce large pieces that can be assembled into bigger structures or come up with entire units such as rooms or houses. These big printers are often concrete printers and here lots of questions remain on how to integrate steel bars with this method. Another alternative and more flexible solution - the combination of robotics and AM technology - comes into play when the pieces are bigger than the printers (see box 2). In terms of future value chain development this cross-over between construction, AM and robotics is a highly important evolution.

The large scale printers used to produce big pieces can be large scale cement 3D-printers using a system of extruding wet cement through a nozzle. In addition powder-based 3D-printed cement structures can be made by mixing polymers with cement and fibers to produce very strong, lightweight, high-resolution parts on readily available equipment (UC Berkeley College of Environmental Design). Next to cement and plastic, also other materials are being experimented with such as cellulose or even salt. Full-scale 3D-prints of cellulose- based material show the cross over between forest industry, construction and AM.

[800] Source: http://www.freeformconstruction.com/partners.php
[801] Source: http://3dprint.com/6340/minibuilders-3d-print-robots/

Box 54: Contour Crafting and its commercial application (University of Southern California)

At The University of Southern California, Professor Behrokh Khoshnevis has built a colossal 3D-printer that can build a house in 24 hours. Khoshnevis's robot comes equipped with a nozzle that spews out concrete and can build a home based on a set computer pattern. The technology, known as Contour Crafting, could completely revolutionize the construction industry. Workers would lay down two rails for the robot to operate on. From there, the Contour Crafting system would glide along the rails and lay down cement. Once that part of the process is finished, humans would do the rest of essential tasks like hanging doors and installing windows. Contour Crafting could also reduce the total cost of owning a home. It could also make it easier to repair homes damaged by devastating weather events.[802]

Most AM materials for construction use can be divided into three categories: plastics, concrete and metal. Because of safety reasons plastic houses will not be accepted by regulation. Most of the activities that relates to building houses have focused on printers that use concrete. The most popular building printing technology has been the USA based contour crafting launched almost 20 years ago by Behrokh Khoshnevis (see box 3) but due to patents and related projects behind closed doors it is not clear what is the market scope of this research (interview Salet). Some living lab examples based on this technology have been produced by the company of Andrei Rudenko. Alternative printing technologies were launched by Enrico Dini of D-Shape in Italy. He is developing a system based on 3D-printing, in which a layer of stone powder is deposited, and a binder is printed onto the power, solidifying where it prints. The result is a large-scale structure made out of reconstituted stone. Most advanced technologies focus on the scale up of metal structures for the construction sector at the moment.

[802] Source : http://www.collective-evolution.com/2014/02/22/scientists-develop-giant-3d-printer-that-can-build-a-house-in-24-hours/

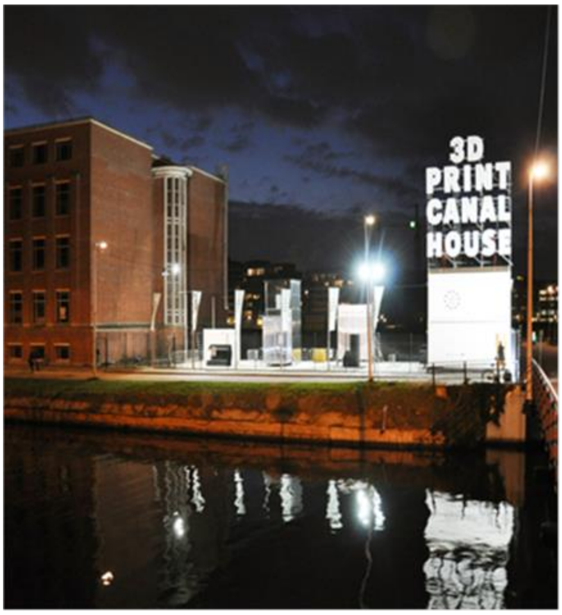
4.2.9.2 Identifying value chain components

(i) Identification of key players and usage of Additive Manufacturing

3D-printing technologies are being adapted for use by the construction industry to create buildings and other structures. In Europe the use of additive manufacturing for affordable housing is still in its early stages and no new value chains are operational at this point due to the fact that no markets exist yet. However, as it is expected that markets will be created in 5 to 10 years (interview Bier, interview Jähne) several RTO's are active in the field and in certain cases industrial players have joined them as material, printer, robotics or construction experts. In addition the first start-ups have been created in the field and most promising ones already attracted the attention of overseas investors. Before zooming in on the players in the field and their position in the supply and value chain, a selection of key pioneering AM affordable housing or directly related projects will be discussed.

The starting pistol was fired by Dutch studio Universe Architecture, who, in January 2013, unveiled designs for a looping two-storey house that resembles a Möbius strip and will be printed on site, in concrete. Shortly after, UK architects Softkill Design announced plans for Protohouse 2.0, a single-storey dwelling with a fibrous structure resembling bone growth. It will be made of plastic and printed in a factory, in sections that are then snapped together on site. Then DUS Architects, went public with a project to print, room by room, a canal house in Amsterdam (see), using a homemade portable printer located inside an upended shipping container. The Canal house projects aim is to learn about the technical issues and possibilities. One issue is how to make a safe house that does not melt and another how to print different materials at the same time. The way forward seems to be better heat resistant materials and 3D façade panels, 3D formwork such as 3D construction poles filled with concrete. New materials will appear and new ways of printing (new printers, new printing techniques). The strength is that all can be customized. However, it will take another 5 years before there are any 3DP building products (façade, toilet) on the market. The ultimate aim is to print small houses.

Figure 142: The 3D-printed Canal House in Amsterdam



Source: *http://3dprintcanalhouse.com*

Another famous Dutch example is the canal bridge project by MX3D. This project is relevant for the affordable housing application as it develops a better understanding of how AM metal techniques can be developed to produce concrete reinforcement structures. The MX3D system employs industrial robots to build structures additively. The robot's arms are fitted with specially developed welding heads. Instead of producing blobs of molten metal to join parts together, the robots, in effect, keep welding—adding one drop of weld on top of another, and "drawing" out long rods of steel. To print the bridge, the robots will either sit on it, printing their own support structure as they go, or operate from barges moored on the canal below. Either way, the process is likely to take about three months. The project is being supported by Autodesk, an American producer of design and engineering software; Heijmans, a Dutch construction firm; and ABB, a Swiss-based maker of industrial robots[803]. This steel bridge is a strong niche product that enables customized design.

[803] See http://www.economist.com/news/technology-quarterly/21662647-civil-engineering-3d-printing-technologies-are-being-adapted-use

Box 55: Heijmans a pro-active construction company in 3DP and innovation

The Dutch construction company Heijmans has been involved in the above described canal house and canal bridge projects and they should be seen as an example of a construction company actively supporting AM solutions both with sponsorship and in-house knowledge. Heijmans further believes concrete is not an option as it is an old fashioned polluting material that does cause too much CO2 emissions. They see a need for new materials and are working together with BASF from Germany to screen new ingredients and the requirements of products. New materials and new big printers that can produce big pieces to be assembled will change the industry[804].

While the above key European example involves only plastics and metals, especially printing concrete is currently being investigated. For example, a group from the UK's Loughborough University (UK) has demonstrated technology which is based on printing cement based mortar. The team is currently working on producing concrete components with dimensions of up to 2 x 2.5 x 5 m and has worked with several construction companies. It is now exploring ways to take the technology from the lab into a genuine construction environment (http://3dprinting.com/3dprinters/3d-concrete-printing-project-3dcp/). Universe Architecture is collaborating on its Landscape House with Enrico Dini, Italian robotics engineer and founder of Monolite UK Ltd. With its D-shape technology Monolite UK Ltd. aims at the construction industry. Dini invented an extremely large-format 3D-printer that uses sand and a chemical binding agent to create a stone-like material that can fit within a cube with sides 6 x 6 m. The machine, called D-Shape, is located in a warehouse near Pisa and works like a laser-sintering machine, but with sand instead of nylon powder, and chemicals instead of a laser. A moving horizontal gantry first deposits a 5mm substrate layer of sand mixed with magnesium oxide, then, via a row of nozzles, squirts chlorine onto the areas of sand that are to become solid. This resulting chemical reaction creates synthetic sandstone. (http://www.dezeen.com/2013/05/21/3D-printing-architecture-print-shift/). Furthermore the TU Eindhoven research is looking into the role of concrete.

Box 56: The Chinese 3DP concrete houses and the pioneering role of the Winsun company

Winsun is a Chinese high-tech enterprise that is engaged in the research and development of the new materials for construction. It currently owns more than 90 national patent certificates. Winsun was published as the world first high-tech enterprise that could truly print 3D houses and put forth six breakthroughs of world leading technology and application. At the same time, in Shanghai Qingpu Science Park, it also represented 10 full-sized 3D-printed houses printed by its world biggest 3D-printers. Its 3D-printing technology is expected to revolt construction, estate and even more industries. However lots of challenges remain to be solved[805].

At the TU Delft researchers are currently investigating additive robotic production. The team investigates robot additive and subtractive design to production experiments (with ABB and KUKA, a robotics firm from Germany). The aim is to find out how one can improve performance of buildings by using robotic techniques. In addition the team studies how one can scale up and use robotic techniques at a building scale. A next step according to Henriette Bier from the TU Delft is to try to build a one-to-one prototype of an enclosed building such as a student housing unit. Additive robotic production is going to be for certain parts of the building, not for all parts of the building. In principle, a house consists of various components that are made of different materials. Therefore, the research team in the TU Delft is looking into multimode robotic production at the moment. Basically, additive is only a part of the process. It includes also subtractive and transformative techniques. (Interview with Bier)

Box 57: The Contour crafting inventions from the US acknowledged as disruptive technologies

In 2014 Contour Crafting invention from the USA (see also box 3) received the Grand Prize among 1000+ globally competing technologies in the Create the Future Design Contest which was organized by the NASA TechBriefs Group. Contour Crafting was earlier selected as one of the top 25 out of more than 4000 candidate inventions by the History Channel Modern Marvels program and the National Inventor's Hall of Fame; and has been identified as one of the major disruptive technologies of our time[806].

However, at this early stages of development, the use of additive manufacturing for the construction of houses and other large scale structures remains focused on prototyping and learning experiments. Most interviewees underline that construction companies are very conservative and that they are little involved with additive manufacturing. Known exceptions here are Heijmans from the Netherlands and SKANSKA from Sweden. Specialized companies have been working on AM technologies for Offshore, Defense and Space creating potential spill-overs to the regular construction sector.

[804] Source: Interview Krug, Interview Salet.
[805] Sources: http://factor-tech.com/3d-printing/3421-are-3d-printed-houses-practical-the-experts-weigh-in/ and http://www.yhbm.com/
[806] Source: http://www.contourcrafting.org/

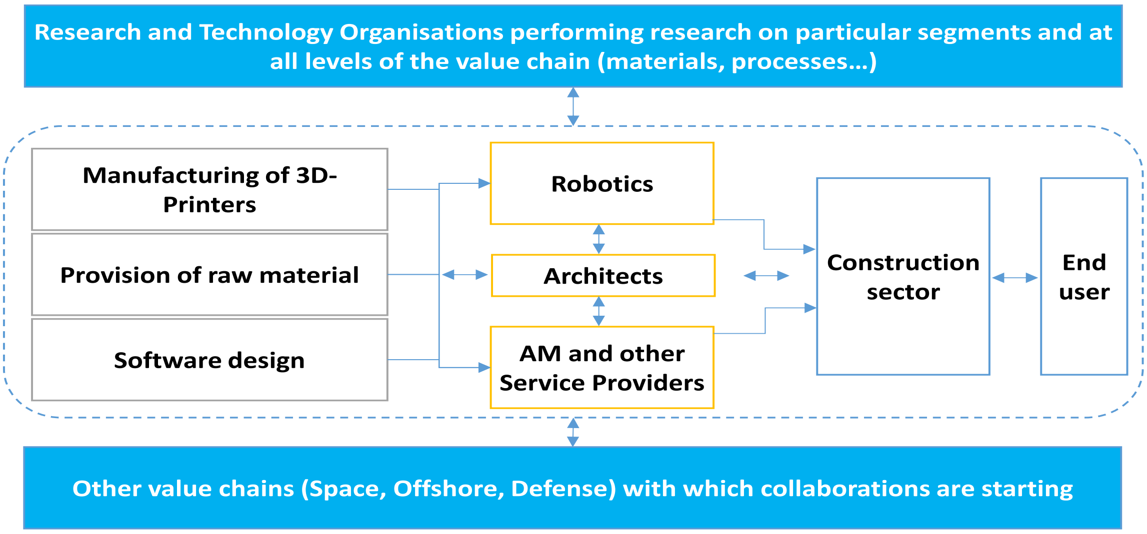
The "gate keeper" approach proved to be fruitful, but using it, we also encountered some limitations: the strategic value of the information sought led several contacts in the industry to decline our invitations to discuss, due to the too strategic value of the information requested. In addition, a certain fatigue was expressed by corporate and technical contact points in the companies who are dealing with a number of similar enquiries linked to European but also national studies on Additive Manufacturing.

(ii) Composition of the value chain

In order to better understand the status of additive manufacturing for the application affordable houses, the value chain is reconstructed in order to position the key actors who are active in Europe but also (to a more limited extent) outside Europe. Most actors involved in the additive manufacturing of affordable houses are located in the Netherlands (North Holland, South Holland, North Brabant, Utrecht), the UK (London, North-West England, West-Midlands, East Midlands, South-East England), Germany (Bavaria, Hessen, Baden-Württemberg, Rheinland-Palatinate, Nordrhein-Westfalen) and Switzerland (Zürich). Key players are also located in Italy (Tuscany), Sweden (Västerbotten, Skåne), Belgium (Flanders) and Finland (Uusimaa, South-Carelia). A more detailed list of players identified is available in Annex 13.

Figure 146 illustrates how a value chain in the AM construction of affordable houses could look like based on the available evidence at these early stages of development. In can be expected that the construction value chain will take on board new players which are companies specializing in additive manufacturing and robotics. In addition the role of the users will be more pronounced (Interview Krug). In order to make the involvement of key players clear along this value chain, Figure 145 provides more detailed examples on which segment(s) particular organizations are active.

Figure 143: Main segments of the construction of affordable houses manufacturing AM value chain



Research and Technology Organisations. Due to the early development stages of AM in the construction of affordable houses application field, almost all activities observed are pure research or in some cases applied research in collaboration with the industry. Several collaboration agreements with RTOs can be identified in the area of additive manufacturing for construction. Among these, TNO, VTT, TU Delft, TU Eindhoven, University of Darmstadt, Umeå University, Lund University, IAAC, and ETHZ, some are clearly in a lead position in Europe, such as ETHZ as they collaborate with the private sector on strategic research. Among the topics investigated, the most popular seem to touch upon how AM, robotics and automation can change the way things are done in the construction sector. Though all the research teams have the same objective, the teams are investigating very different materials and fabrication methods (interview Geurtjens).

Manufacturing of 3D-Printers. On top of the value chain are the software and materials providers, and the 3D-Printer providers (Interview Frances). As described earlier in the context of the construction sector, one has to distinguish between smaller traditional 3D-Printers for small components and big printers for big components. For the construction of mega components or entire structures there is a new trend to investigate the use of robots and automation (Interview Bier, interview Jähne, interview Salet). Although it is not always clear to distinguish between robots and printers, in this report robotics has been treated as a separate value chain category as to underline its potential importance for the future of the activities under analysis (see Figure 3). Players such as the TU Delft University pointed out they are not using 3DP printers but robotic devices to 3D-print. They are working with KUKA and ABB because robots can do any kind of operation that is required. The assumption is that you are not only going to use 3D-printing but a whole set of different operations into the building process. In the factory of the future, they see the building process completely robotized. Alternatively robotics could be included in the 3DP category or appear as another value chain with which collaboration has started.

In Europe most important printer/robot projects are D-Shape of the firm Monolite (Tuscany [IT] and London [UK])[807], 3DCP[808] (East Midlands [UK]), and MX3D[809] (Noord-Holand [NL]) while from the US the Contour Crafting[810] technology is seen as important (California [USA]). Other interesting European printer projects are KamerMaker (DUS Architects and Ultimaker, NL), TU Eindhoven and ROHACO concrete printer (NL)[811], Betabram[812] (SI) and some (conceptual) projects at IAAC (Catalonia, Spain) and ETHZ (Zürich, Switzerland) and the printing heads/systems of .G.tecz Engineering GmbH (DE).

Provision of raw material. The materials in the research and development projects are provided by companies that are specialized in different areas. In the field of construction there is a vast diversity in materials, such as concrete, tarmac, wood and steel. This entails concrete spraying, resins and (bio) plastics (provided by companies such as Henkel) and metal powders and welding material (provided by companies such as Arcelor Mittal). In the early stages of development of AM for the construction of affordable houses, material providers have a keen interest to develop new and different materials that fit the requirements of the new printers and robotics being developed. Promising research projects in the field often take material suppliers on board to look for new innovative solutions (see for example G.tecz Engineering GmbH). Material providers are usually large companies from bigger countries such as Germany (such as Henkel and BASF) and UK (LaFarge Tarmac). One key challenge for the field is that materials should still be developed that can be processed on printers or contour crafting machines and that can fit the requirement of the building industry. The best system doesn't help you if you can't process good materials (Interview Zimmermann). Some experts foresee that materials are going to be customized, meaning that all parts of the system are changing. Material will be prepared and transformed according to the user needs and required performance. Customization is starting from material to process and product eventually. (Interview with Bier)

Software design. Software plays a key role in the research projects. MX3D stated for example that 70% of what they do is software (interview with Geurtjens). This also suggests that the value added will be very much into the software. Looking for the right materials and hardware in form of printers and or robotics is important but to automate all of these one needs to put major attention to software development. In Europe you see that new software development in the field happens either at universities or at spin-offs (for example ROB Technologies AG in CH) and start-ups (for example MX3D in NL). A trend here is that big software players from the USA are buying promising European start-ups. In example of this overseas acquisition strategy is WithinLab from the UK that was bought by Autodesk. Other big players in the field have been Materialise from Belgium. As software offers the platform for value creation these acquisitions are not a priori positive for Europe.

Robotics. In the above printer section it was underlined that it is not always straightforward to distinguish between a printer and a robot. As experts pointed out robotics are already playing a key role in the development of the construction sector (Interview Bier, Interview Jähne) we decided to treat robotics as a separate category in the value chain. Architects are envisioning a change in how robots will be used in the future and this has also pushed forward the research in the field (see Figure 4 for an overview of European projects). The key players from the industrial robots industry that have been active in the construction field are KUKA from Germany and ABB from Switzerland. In addition also Stäubli from Switzerland and to a lesser degree Comau from Italy and Fanuc from Japan have worked on robots for the construction industry.

Architects. For the future formation of the value chain architects have been playing a key role as drivers of new concepts and innovation and research (Interview Geurtjens, Interview Bier, Interview Salet, Interview Jähne). In that role they can influence all the other key players in how the value chain will eventually look like. The architects are able to design complex shapes which they however can't currently effectively make. (Interview with Francis) People at IAAC in Spain, at architect practices in London and at the ETHZ in Zürich are important to mention here. Also some US players such as the Jenny Sabin Studio and Kushner Studios have contributed to this field.

[807] Source: http://www.d-shape.com/index.htm
[808] Source: http://www.freeformconstruction.com/
[809]Source: http://www.economist.com/news/technology-quarterly/21662647-civil-engineering-3d-printing-technologies-are-being-adapted-use
[810] Source: http://www.contourcrafting.org/
[811] Source: https://www.tue.nl/en/university/news-and-press/news/22-10-2015-tu-eindhoven-starts-using-kingsize-3d-concrete-printer/
[812] Source: https://all3dp.com/rise-3d-printed-personal-house/

Figure 144: European Map of the Robots in Architecture players.

Source: Association for Robots in Architecture: *http://www.robotsinarchitecture.org/map-of-creative-robots*

Additive Manufacturing and other service providers. Big players that have worked for the European construction sector in this field are Materialise (BE) and 3D Systems (USA) and EOS (DE). Players such as Z Corp (USA) and CRDM (UK) have recently been bought by 3D Systems[813]. In addition Emerging Objects (US) has been a key player, especially in the US. The 3D-printing service providers cooperate with Architects. Other service providers have been based in the UK, such as Shotcrete Services Ltd. (concrete spraying solutions) and Buchan concrete Solutions and Bureau Happold. They may also be part of the value chain with the construction sector category.

Construction sector. The construction sector and building of houses are in essence very traditional industrial areas (Interview Krug, Interview Salet). There are some examples of traditional construction firms that have engaged in research projects on 3DP such Heijmans (NL) and Skanska (SE). Also the traditional material providers of the construction have been involved in research projects either as sponsors or as knowledge providers.

Connections with other value chains. Another dimension is the existence of cross-value chain cooperation. The D-Shape concept from Monolite UK Ltd has gotten attention from Areospace research and industry. It is envisioned that buildings will be printed on the moon with moon dust[814]. The construction of cheap buildings can further be of interest to the defense industry if troops have to be stationed or war zone migrant streams have to be taken care of[815]. Furthermore methods developed to build metal structures for building can also benefit the offshore industries (Interview Geurtjens).

Currently no international markets for AM based affordable housing exist yet. Due to the lack of regulation China has an advantage in being the first to have a market for AM developed houses. Furthermore, as the contour crafting method development has been surrounded by secrecy and very many patents it is not clear how close to market these developments are (Interview Salet). It was stressed by the experts that the work being done in Asia is interesting but that the cultures are so different. In Asia there are a lot of people, small houses and skyscrapers for which automation such as tile laying robots are possible. At this point is not foreseen that similar ways of working could be applied in Europe. Because of great government support and a more organized approach the leading players in the field of additive manufacturing (AM) in construction are Singapore, Switzerland and USA. EU countries are lacking behind here and research activities are reduced to a few individuals.

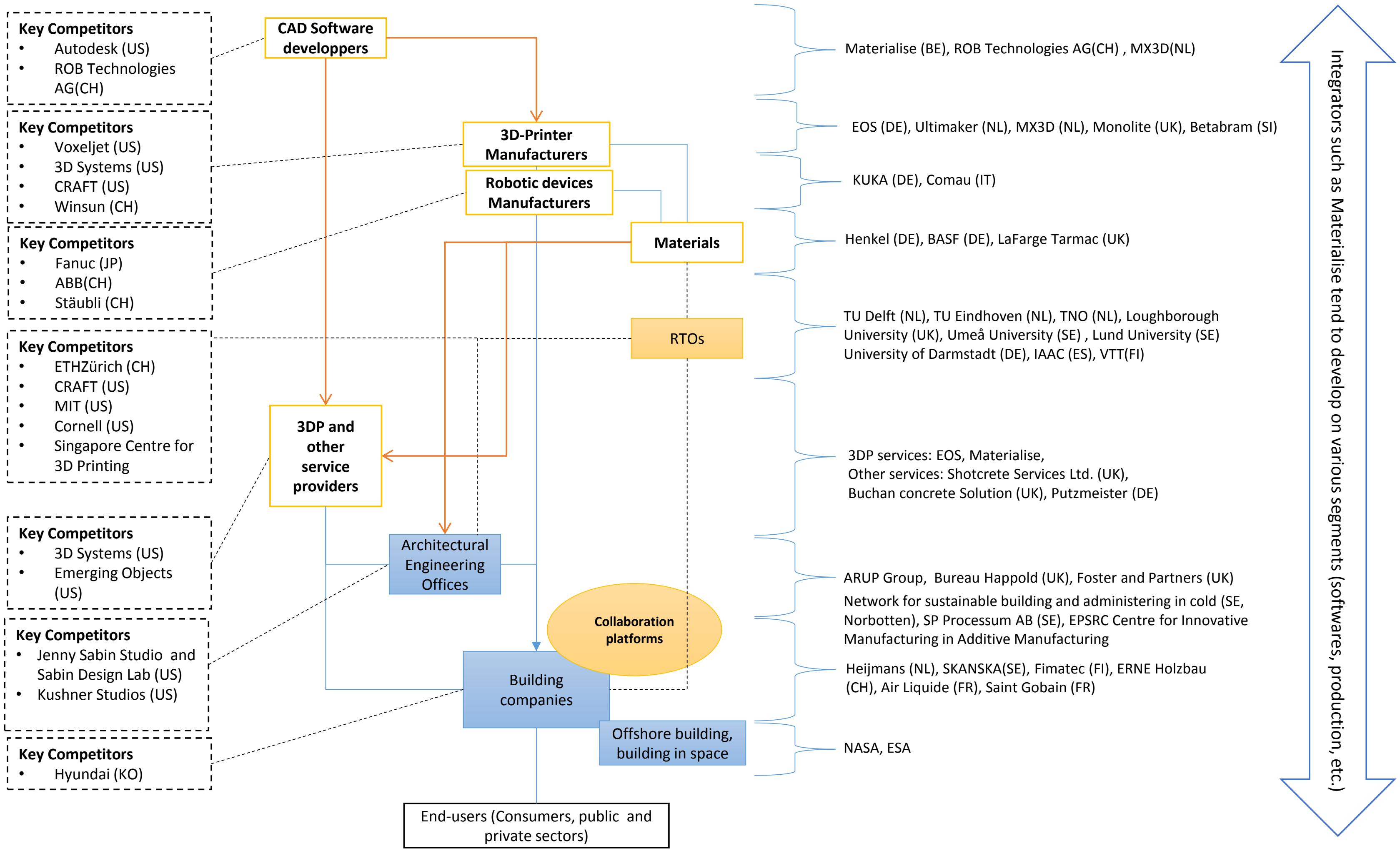
As was also observed in other AM application fields also in our case big US players (Autodesk and 3D systems) have been acquiring several European targets in the field (see above) and we do not foresee any changes here once activities are starting to show more market potential.

[813] Sources: http://www.3dsystems.com/press-releases/3d-systems-completes-acquisition-z-corp-and-vidar and http://optics.org/news/4/8/25

[814] Source: http://thecreatorsproject.vice.com/blog/3d-printing-buildings-from-moon-dust

[815] Source: http://3dprint.com/107627/3d-printing-sustainable-aid/

Figure 145: Illustration of the affordable houses additive manufacturing emerging value chain



Note: the names of the organisations mentioned are only included for illustration purposes and no colour code was applied – colours codes were only added to make the figure more readable.

(iii) Functioning of the value chain and critical factors

Based on our desk analysis and first interview rounds it has become clear that the value chain *affordable houses additive manufacturing* is not existent yet or at best at a very early stage of development. In general AM developments have only recently started in the construction sector and activities are mainly focused on research and prototyping. Markets are only expected to take off in 5 to 10 years (Interview Bier, Interview Jähne). These early stages of development also mean it is not always possible or appropriate to distinguish between different AM applications in the construction sector. Indeed, experts sometimes did distinguish between affordable housing and other construction activities but often stayed on a general construction sector level. In the majority of cases experts could not offer specific information on value chains.

In some case the construction industry can be quite diverse consisting out of a very fragmented landscape with lots of suppliers in the chain. This means that it is not easy to get partners to invest in R&D and that the budget are often too small to make the difference. R&D investments in construction are peanuts compared to what happens in automotive or aerospace for example. In construction there is no coordinated approach investing in technology. Therefore setting up projects to realize new big ideas are not easy to realize. In general one can also sense research would need more support from industry and that close links not always exist.

For the researchers and practitioners in this field, there are two grand challenges in solving problems. The first challenge relates the production of components in pre-fabrication. For pre-fabrication a computerized assembly line is needed that is easy to automate. For this pre-formation stage light materials such as wood are preferred as they are easier to transport then for example concrete. The second challenge relates to onsite construction. On site construction requires on site robotics interacting with humans. This context is much more complex (than for example a car factory assembly line) and finding solutions much more challenging (Interview Jähne).

The real challenge for value to be created and pumped into value chains is scale up, because buildings are not small objects. Indeed, a certain amount of skepticism remains regarding the viability of scaling up AM technology that, until now, has only been used to make relatively small objects – objects that do not demand the structural or environmental performance of a house. However, architects working in this area have been playing a crucial role in researching new concepts and thinking of the role AM can play in transforming the construction and housing sector. Architects do see a future key role for AD in construction. However, the speed of digital manufacturing, not only characterized by AD but also by robotics and automation, often contrasts with the very traditional and slowly changing construction sector. The difference in cultures is a real challenge and bridging those will need time. How can one let architects work together with computer scientists and robotics people in an optimal way (Interview Jähne, Interview Francis)? Value chain development cannot happen without having the right people with the right skills (design, I.T. Construction) and therefore there is a role to play for education and training sector here. Who will be reprogramming the robots with AM printers on the construction sites? Who will be bridging the gap between different industrial cultures?

Furthermore it should be underlined that digital fabrication will transform the construction sector and that AD is only a part of that. Not all components of houses will be made by AM and not all components will be 3D-printed. Robotics will play a very important role in this digital revolution and therefore in the construction sector. AM should be seen in this broader digitalization and automation context.

The majority of the building industry is very reluctant to start with AM and other new technologies because it is going to change completely the structure of the production and marketing and sales, buying, selling. Everything is going to change dramatically. AM technology will disrupt the landscape. New companies popping up for support planning and construction site (CAD model design will be bought by established big players). Because of the economic situation all players want to cut costs. Currently lots of money is being made by correcting mistakes in the planning. With 3DPlanning all the mistakes will disappear. However, more hours and money will be put to planning and less money will be put to construction itself. Overall productivity will rise and costs will be cut. We evaluate towards cheap methods and cheap mass production. This evolution will obviously impact the value chain. Another important factor that will have a big impact on the value chain is that users will be much more involved in the co-creation and – production of buildings.

Some of the experts however do expect that in the very traditional and slow moving construction sector the set of very homogeneous players will become more diverse. Some of the players will stay traditional and some other players are pushed to innovate more. If you do not innovate you cannot become the next big winner. The market for traditional players will not collapse because they make things based on lean processes and initially they will be able to be cheaper than 3DP materials. Concrete will still be important for building affordable houses.

Once technology does allow scale-up, regulation actually forms another barrier to cross for markets to be developed and value to be created. National and European regulation and policy is lacking behind and it is not at all clear if regulation will be adapted as to scale-up living lab experiments into real commercial products. Indeed, a concern that throws a shadow over the digitalization is that it is expected to cost many jobs in the construction sector.

To conclude in the words of Sköld and Vidarsson (2015) "factors that are gonna be crucial for the development of AM in the construction industry are the (1) Importance of having a collaborative approach, (2) Incentives for investing in the AM technology, (3) Standards in AM and (4) Maturity of the AM technology in the construction sector". This should be the focus of further research.

4.2.9.3 Missing capabilities

(i) Regional dimension and missing capabilities

Looking at the regional dimension of the case study "affordable houses additive manufacturing", one can notice that the existing capabilities are concentrated in a few ecosystems in Western European countries. Overall there are many players having some or serious activities in the field, but many of those seem to work on their own without taking into account too much what is going on in other European countries and globally. We list the regional distribution of the most coordinated and influential actions in Europe so far.

The Netherlands (more specifically North Holland, South Holland, North Brabant, Utrecht) has already produced several visible research and prototype projects in the field. The technical universities of Eindhoven (with RODAHO from Utrecht) and Delft and TNO have been active in research. Projects such as the canal house (DUS Architects and Ultimaker) and the canal bridge (MX3D) in Amsterdam have revealed capabilities and technical challenges to be taken care off. Construction company Heijmans has been actively looking for renewal through 3DP technologies. The Dutch players work also together on material development and robotics with big established German companies (materials from Henkel, BASF and robots from KUKA and the Swiss ABB). In Germany significant supplier firms and some active engineering firms (such as G.tecz Engineering GmbH) are based in Bavaria, Hessen, Baden-Württemberg, Rheinland-Palatinate, Nordrhein-Westfalen(see list 2.3).

Other significant activities have been concentrated in the UK (more specifically in London, North-West England, West-Midlands, East Midlands, South-East England). Loughborough University has worked on concrete printing with partners from industry such as the Swedish construction firm Skanska, architects Foster and Partners, material developers Buchan concrete and Lafarge tarmac and Swiss industrial robotics company ABB. In London several architectural offices and consultancies are based and several prototypes of 3DP based living units have been developed.

In Northern Europe Swedish universities that entered this arena are from Lund (Skåne) and Umea (Västerbotten). Skanska has cooperated with partners from Sweden and the UK. In Finland VTT and a few start-ups (Fimatec) have been active.

Last but not least the work of Dini on D-Shape printer in Italy's Pisa area (Tuscany) has been influential in Europe and can be seen as an alternative model to the contour crafting technique launched on the US West coast. Also in Barcelona in Spain (Catalonia) the architects have worked on important conceptual work in the field.

However, maybe the most important work in Europe has been concentrated in and around ETHZ (Zürich, Switzerland).

From the above landscape one can actually see that in Europe only few concentrations of activities exist and that overall we see scattered activities what gives room for improvement as by default a minimum scale has to be reached to make a difference. It is striking that for our case no activities and capabilities exist in Eastern European countries with the company BetAbram from Slovenia, a producer of big concrete printers, being the only exception we managed to trace down.

In order to summarize the identified critical missing capabilities:

- Overall the 3DP activities related to affordable housing are **scattered** over Europe with only few countries and some of their regions that do well such as the Netherlands and the UK. **To reach critical mass it would be beneficial to bundle forces**.
- Eastern-Europe seems not to have activities in this field apart from some SMEs activities from Slovenia. A majority of the most important activities seem to be concentrated in **Western Europe** (German speaking regions for material development and robotics, UK and the Netherlands).
- One additional missing capability is not technological but relates to the **financing and ownership strategies** of promising ventures especially in the fields of design and software development. It seems that the continuity of European ownership is not always realized in this field what may potentially hamper optimal growth of the company targets and their European ecosystems.
- Furthermore even and especially in countries that are active in the field there seems to be **a need for 'bridging people'** that understand robotics, software and the construction sector as to make development projects more successful.

(ii) Barriers to uptake and further deployment of AM in value chain

Before listing the barriers, we underline that the role of AM in the construction sector and for the production of affordable houses is currently still at an early stage and that we mainly see a concentration of activities in research and prototyping.

Mentality, information and awareness

An important barrier of uptake and further development of AM in the construction sector is the fact that the **construction sector has been very conservative** and **slow in uptake of new technologies**. During the last 30 years no real big innovations have renewed the industry and this is a real challenge and clear barrier. The sector does not easily accept new ways of working and new technologies and there is not a lot of diversity in terms of the background of people. The construction sector is also **cautious** to start using these new technologies as it is going to change completely the structure of the production, buying, selling. Everything is going to change dramatically. Actually, the user will be much more involved in the co-creation of buildings. It will have a huge impact on the building industry and the value chain.

Although lots of activities in the construction sector are concentrated around concrete components, some players think concrete is not an option as it is an old fashioned polluting material that does cause too much CO2 emissions. For the long term image of 3DP **it is critical to be transparent about how sustainable the 3DP activities for construction are**. To overcome this barrier coming up with new sustainable materials may be the way forward. Another step in the good direction is to recycle waste materials as an input for 3DP building components. The public sector could play a role in **raising awareness** for 3DP in the construction sector.

Value chain specific dynamics

In addition, **standardization** is a critical issue for 3DP activities to take off. Several materials used for 3DP are currently being investigated and their properties are actually not known yet, meaning that standardisation can only happen at a later stage. Furthermore, it is difficult to know how 3D-printed materials perform over time, and how various used materials react chemically. Furthermore it is hard to know how printed materials will react with other materials.

Another barrier relates to **building regulations** that are very strict. Producers of 3DP affordable houses have to take care of **safety** and therefore regulators have to agree that new materials and processes can create safe buildings. In the case of plastics for example the problem is that they are not heat resistant in the case of a fire and this also applies to wood.

The most popular building printing technology has been the USA based contour crafting launched almost 20 years ago by Behrokh Khoshnevis but due to patents and related projects behind closed doors it is not clear what is the market scope of this research. **IPR**'s will play a key role in deciding who will have how much access to future markets.

Further looking through the lense of value chain shows us that the vast majority of the 3DP value added in this sector will come from design and software. In general 3DP technology is indeed enhancing the design approach. To capture value it is crucial that Europe builds up capabilities in design and software development. **This means that one should develop platform companies and think in an ecosystemic way**. One barrier for the design take-off is that these skills have to be fostered more and that there should be sustainable ownership strategies for ventures in the field.

A final value chain challenge for 3DP to take of in the construction sector is that is that the **costs are still pretty high and the volumes pretty low** what does put a burden on market development.

Knowledge

One important barrier is to come up with the right materials that fit the purpose and that can even be custom based. Moreover very often excellent systems cannot create the necessary value if they cannot process the good materials. The development of a range of materials with their requirements will ask lots of time investment in research but also in marketing.

Customization is a clear trend that is starting from material to process and product eventually. We need more knowledge on how to do that. Lead users will play a key role in customisation and design practices. A step in the good direction could be the use of printers for designing and renovating the house after it has been build. **Knowhow in customisation practices should be fostered**.

New business models should be investigated by the sector. Online applications will appear where clients can customize their houses**.** There is potential within logistics, software, machinery and hundreds of new types of services. There is a chance that we might see some totally new companies and business models, that hopefully will take over conservative companies that are not good at adopting new innovations. Missing capabilities could be filled in by new ventures. It is expected that there will be many smaller actors in the field of 3D-printing and the construction industry. The way value chains will develop depends to a great extent on incremental versus disruptive innovations and on the role of incumbents versus that of new ventures. In European context there is a **new role for creative entrepreneurial people** who are related for instance to IT and architecture, who can create new types of services. There is potential in IT, design and creativity, these combinations are relevant within 3DP and construction industry. Entrepreneurs can tackle key issues such as **culture and design**, **IT and gaming**, **infrastructure**, **safety thinking** (related to housing issues), **standardization**, **sustainability**.

Technological performance

For the construction researchers and practitioners, there are **two grand challenges in solving technological problems**: (1) The **pre fabrication** where you need easy to automate assembly line computers. For the pre-formation stage one can use wood as it is light while concrete is heavy and difficult to transport. (2) The **onsite construction** where you bring robotics on site that interact with humans. It is clear that the onsite context is much more complex than the situation at a car factory assembly line.

Challenge is to scale up, because buildings are not small objects. In principal we are accustomed to have high-risers so how could the technology be scaled up, that's the challenge. How one can we reach big size and good quality is the challenge.

Furthermore it is already clear that 3DP or **additive robotic manufacturing is only gonna be for certain parts of the building** so the scope is maybe smaller as often thought. However currently **it is not fully understood yet when it is optimal to use additive or substractive techniques**. It has to indeed still be found out in which niche markets of construction it makes sense to do 3DP and that based on the costs and alternative methods. The result will be a mix of traditional and conventional methods with 3D-printing technology. There is a firm belief that 3D-printing in concrete will never totally replace high quality precast processes. For some components it will still make sense to keep on precasting them. Key is that 3D-printing offers an opportunity to download data directly into the robot's brain and as such cut process time.

The challenge is to produce and assemble the different components needed to build a house. **Integration** is a challenge of materials and processes. **This requires multiperformative and multimode operations**. Therefore we distinguish two phases in the uptake of 3DP by the construction sector: (1) in the mid-term some parts of houses will be made via 3DP, (2) in the long term one could think of integrated multi-mode methods using different materials, 3DP and new techniques. If you build a building there are many different people and craft and materials and processes involved and we don't expect 3DP to replace it all. 3DP is rather one more thing that will come into construction, but it's not there yet. Robotic devices (that are more flexible than 3D-printers) are going to be used to do all kind of operations, also to 3DP (see for example the factory of the future).

Missing capabilities

Despite the traditional character and the low productivity of the construction sector **researchers and especially architects** have a much more innovative and broad vision about 3DP. In general they talk about the role of digitalisation for the transformation of the construction sector. For them 3DP and other assembling techniques make use of digitalisation and question current building technologies. **The value of architects is their conceptual thinking that can revolutionalize the sector**. They represent a new way of thinking driven by changed processes and new ways of linking design to production and consumption. This concerns a paradigm shift. **Nevertheless more cooperation is needed between different fields for things to really start happening**. To fuel successful cooperation between architects and experts from robotics, software and construction industries, **we need to get more bridge makers and better multidisciplinary capabilities in Europe**. This is a real challenge as this involves shaping new mentalities and new mindsets.

Currently activities are concentrated in scattered research that still needs some work. Industry is not really on board yet. **A tipping point is needed** and will be reached. Once we have the tipping point, things can go fast. **There is a need for coordination and bundling forces as to speed up the research and commercialisation process.**

Currently there is no market yet and that will still take 5 to 10 years. Based on the Gardner hype cycle of technology development one can see that there has been a hype surrounding 3DP but that recently we have seen less interest. It is expected that after 2 years the hype will pick up again. New issues might arise in the future, but forecasts would at this stage remain speculative. IPR were for instance not mentioned as hampering factors in the affordable houses case as the whole field is still very much in its early stage of development focusing mainly on research and still far from the commercialisation stages. IPR in 3D-printed affordable houses relates to design rights but also to patents on 3D printing technologies. It was mentioned that the US based patent portfolio related to contour crafting 3D-printing technique is extensive and may play a key role in the future market developments. In addition it can be expected that design rights for housing will play a role in the future.

Overall it is meaningful for the affordable houses case that the IPR issues were only brought up by one expert. Development of strong US based patent portfolio's related to 3DP-affordable housing, the use of mergers and acquisitions for acquiring IPRs of European players and the fact that IPR is taken less seriously in China are all issues that should be followed up closely. It can be expected that all these issues may potentially harm the strategic role Europe could play in the field. But this development remains dependent on the evolution of the technology and related market.

4.2.9.4 Conclusion: opportunities for public support

The role of AM in the construction sector and for the production of affordable houses is currently still at a very early stage. For fostering the development of 3DP in the construction sector and for the production of affordable houses the public support should focus on offering the right framework conditions. In addition the role of public policy is to raise awareness in the concerned sectors and to push the development of capabilities. In some cases public policy could act as an orchestrator as to make sure European ecosystems can be nurtured and grow. Based on this study we distilled 7 key policy related conclusions:

(1) First of all there seems to be certain key capabilities that are currently missing in Europe. **National education and training policies should focus on making sure we have people that understand multiple fields** such as robotics, software and construction. In addition lots of attention should be paid to delivering people that can contribute to where the value is created, meaning **design and software** development.

(2) In addition national and EU policies should **focus on the creation of platforms and ecosystems that can create the value**. Very often value is concentrated around a very few firms and it means that one has to foster these platform firms to grow and to create a value based ecosystem.

(3) In the construction sector there are several thousands of suppliers in the supply chain. Therefore getting a common approach to invest in 3DP related innovation is very cumbersome. For example the automotive industry and the aerospace industry have huge R&D investments compared to what construction does. **So a coordinated approach is needed in such a scattered landscape to invest in technology**. It is of importance to aim at concentrating the scattered landscape of research on the topic in Europe. Only by focusing on critical mass we can make a difference and this has clearly been stated by the experts. Because of great government support and a more organized approach the leading players in the field of additive manufacturing (AM) in construction are Singapore, Switzerland and USA. EU countries are lacking behind here and significant research activities are reduced to a few individuals. **More ambitious financing programs both at national and European level are a condition for more ambitious research and innovation outcomes.** Moreover in national policies attention should be paid to ensuring the **access to finance** enabling the **uptake of new technologies** and the coverage of the related initial **costs of adoption**.

(4) Another issue that relates to financing is that some fruitful companies are in the target of being bought. **This requires global M&A strategies (merger and acquisition) from Europe as not to loose its best pieces to competitors much too early**. Typically it is the platform companies that are bought and slip out of European hands. Moreover the best firms have often strong IPR portfolio's. For policy monitoring acquisitions can give insights in IPR development and concentration. Special attention should be paid to US and Chinese IPR portfolio dynamics. However, as the 3D-printed affordable houses field is still in its infancy stage policy attention should mainly focus on the creation of strong European IPRs by bundling ressources (see previous point 3).

(5) **Further attention should be paid to which cooperation models between industry and RTO's are optimal both on European and national levels**. Especially the building industry has often been reluctant to innovate and therefore universities often feel that private firms in the sector do not take their full responsibility in making sufficient research investments for the future. In comparison with the USA European universities are more independent but also lack the funds that industry could have provided in case that cooperation model would be following the US model based on strong university alumni networks that reach far into industries.

(6) What you will see in the construction sector, a very traditional slowly moving sector, is that a set of very homogeneous players will become **more diverse**. Some of the players will stay traditional and some other players are pushed to innovate more, and innovation is crucial to conquer new markets The market for traditional players will not collapse because they make things based on lean processes and initially they will be able to be cheaper than 3DP materials. **Policy makers both on European and national levels should take a position on how to encourage innovative behaviour in the construction sector and on how to discourage harmful conservative mentalities.**

(7) And finally, the current **national and European regulation and policies are clearly lacking behind** and it is not at all clear if regulation will be adapted as to scale-up living lab experiments into real commercial products. Indeed, a concern that throws a shadow over the digitalisation such as 3DP is the fear that it will cost many jobs in the construction sector.

(8) Although **IPR** were not spotted as a key issue, they are subject to a key risk: mergers and acquisitions of key IPR loaded players in the field by non-EU companies is indeed a danger for European ones. The acquisition by the Chinese investors from KUKA presented in this case study is a good example of the strong dynamics at hand. **Monitoring acquisitions in the field as to be able to follow where the most important IPR portfolios are and monitor new market dynamics** is therefore important. In this early stage of development of the 3D-printed affordable houses field the role for policy should be to boost meaningful IPRs by bundling resources for top European research.

4.2.10 3D-printed confectionery

4.2.10.1 Scoping

(i) Context

One of the grand challenges for the global food market is the growing demand for food that requires developing sustainable methods for food production, which in turn require increase in the efficiency of food production and processing. To meet the challenges we can expect also at least partial switch to alternative food sources.

The food industry is relatively conservative sector in which most of the development is incremental, for instance in food processing it is aimed at the small improvement of existing technologies or at the replacement of minor steps in the food production chain to increase efficiency. In order to revolutionise the market, much more ambitious steps need to be taken. Currently, one such technology under research in food is 3D-printing, or additive manufacturing (AM), which has proved great potential to be used for the layer wise 3D multi-material food products. Technologies for 3D-printing were originally developed for manufacturing industries to typically process plastics, ceramics and metals. In many cases it is successfully been applied on an industrial scale. Like noted in the interviews (e.g interview with Tuomi), the most relevant applications currently in the food industry are on the industrial automation, like in developing machines to food processing. Therefore, 3D-printed food should not be confused with industrial automation. Hence, 3D technologies have been applied also to food industry to print food, for instance to produce fun shapes but potential for the technology is also seen in more serious food products for consumers with special nutritional and dietary needs. The 3D food printer technology is still very nascent, the first patent application was published in 2007 and the patent landscape is dominated by Chinese (Frost & Sullivan 2015). The expectations for 3D-printing in food are enormous although not realised in full, yet.

One general trend in food sector is the fragmentation that might create new business opportunities around 3D food printing. The benefits of AM in food sector can be seen for instance in high material use efficiency and in production flexibility that allows fast responses to market requirements that both target to minimise food waste in food processing. 3D-printing allows also flexibility to use alternative food ingredients which the industry will face in future to create improved products with respect to nutritional content, health benefits and shelf-life. Furthermore, this is an appealing technology to Europe because it provides the opportunity for both SMEs to produce high added value food products in niche sectors, and the large food companies to achieve high production flexibility. Also new business models are envisaged in related subsectors, like printer recipes, food design files and other kinds of services that all provide interesting market opportunities for companies.

The 3D-printing of food allows freedom of design in terms of the composition, structure and texture but also taste. In food the 3D-printing technology can create unique new products and structures that are difficult to imitate by other methods. However, the 3D food printing is currently largely in research phase worldwide concentrating on improvements of existing technologies in food processing and making food production chain more efficient, which means that the research actors, universities and RTOs are the only value chain actors at the moment. Interesting technologies are however developed to replace larger parts or substitute the complete production processes, and food manufacturers are eagerly following these developments. It has been estimated that various affordable food printers will be on the market in five years. In the late 2015, the most interesting and innovative solutions were developed by start-up companies, both Europe and the US, and the first of these 'kickstarter' projects are expected to materialise in one to two years. The 3D-printing in food is in explorative research phase.

The main technological challenges in 3D-printing of foods are the consistency of food materials not to stick into the printing machine and to retain their form after printing. Another area scientists are currently working with is to mix materials to create tasty products (interviews with van Bommel and Sözer) that would bring the 3D-printed food into new level. Furthermore, in the food sector, the adaptation of 3D-printing is at large integrated into wider on-going trend of robotization of manufacturing. According to company representative (interview with Loponen), as food processing machines develop and production automatizes, some interesting opportunities might emerge.

Current drivers in food 3D-printing are preferences for heathier eating habits and need for personalised diets by sick but the field faces scaling up and cost challenges (Figure 146). The 3D food printing is able to offer personalisation, new shapes, hybrid products, alternative ingredients and ultimately localised or de-centralised production (e.g. in supermarkets). Consumers increasingly want value-added food products that are not only green, safe, healthy, and ethical but also unique and personal.

Figure 146: Driver and challenges for adoption of 3D-printing in food

DRIVERS

- The preference for healthier eating habits
- Saves time and labor in complicated food preparations where delicate designing is involved
- The need for personalized food or diets by the sick or athletes
- The need for better food alternatives for astronauts

CHALLENGES

- Scaling-up problems
- Too costly for the average household to own
- Limited ingredients storage and utilization on current models
- High technical knowledge required to experiment with food and 3D printing
- Public acceptance of consuming 3D printed meat is split
- Consumers' preference for natural and organic products

Source: Frost & Sullivan, 2015

According to VTT Technical Research Centre of Finland Ltd's (VTT) experts (interview with Sözer), 3D food printing offers solutions for automation of cooking (e.g. 3D food vending machines), production of food in challenging spaces like in flights for sterility and taste, nutritional options for people with dietary needs, and also for designer food for its aesthetic value. Major challenges still to solve relate to the need for multi-material printing systems and integration with traditional cooking processes, like baking or boiling. One of the major hindrances is the low printing speed.

Regardless of the various challenges 3D-printing in food has to solve, the technologies are currently being developed in research organisations and universities but also in companies. And, most of all European actors are actively involved in this development, although it being still nascent. The food application area was selected to be presented as case mainly because of potential it offers to food industry and because good European demonstrations and first commercial applications available already. These are though mainly seen in confectionery area, in which the aesthetics and design are driving the adaptation of 3D-printing rather than possibilities for personalised diet, for instance. We also see research activity in more than one region in Europe, although the actual value chains do not yet exist. Within the practitioners and companies the attitude toward 3D-printing in food is curious and eager but at the same time in some of the subfields in the food industry the technology is seen to arrive only in distant future.

This report concentrates on food processing in particular in confectionery field and does not discuss the related fields (like packaging) given that all fields face specific opportunities and challenges of engaging in additive manufacturing.

Figure 147: Illustrative applications of 3D-printed dessert decoration.

Source: Mei Lin[816]

(ii) Application area: 3D-printed confectionery

This case report focuses describing the 3D-printing in food mainly in confectionary sector in which we can observe some initial 3D-printing activities. However, as the 3D-printing in food is largely in exploratory research phase, the discussion in this case report is general and attempts to also describe the possibilities and expectations that are laid to 3D-printing in food rather than describing the realised value chains which are not reality yet in Europe. For this reason, this report touches also another highly promising area, the personalised food for consumers of special dietary needs, like elderly or people suffering from illnesses that is presented as future application area to illustrate the potential areas that 3D-printing in food can lead in future. Furthermore, research in the 3D food printing focuses largely on this latter field. However, both fields are still in very nascent exploratory phase.

Due to the current health and wellness trend in food consumption, the revenue of the European confectionery product market is expected to decrease by 0.3% from 2013 to 2018 (Tosin 2014). In view of the negative associations in confectionery, like tooth decay, obesity and diabetes, there is also increasing governmental intervention, for instance placing regulatory standards. Because of the negative associations related to confectionery products, product innovation and development is vital in this market, and new products are expected in the sugar confectionery market which is likely to experience the biggest growth challenge of the confectionery segments, as it increasingly becomes more challenging for manufacturers to communicate the functional benefits in a sugar product. Functionalities offered by 3D-printing can be used as an opportunity to overcome some of the future challenges. Uniqueness and personalisation that are attainable with 3D-printing may bring advantages into this mature but negative growth experiencing food segment.

The confectionery segment was selected in this study as one of the focus areas for the reason that it is one of the few fields in food industry in which the 3D-printing has already been adopted in some extent. Hence, 3D-printing is not mainstream in the confectionery either. Given that the additive manufacturing in food sector at large is mainly at research phase, the confectionery field offers an opportunity to look at how the potential value chains in food industry can (and will) be formed. The next challenge is though, not only in confectionery but food in general, to go beyond the decoration and use 3D-printing to design products that have a certain texture that cannot be attained using conventional production methods (interview with Schutyser).

The artisanal field of confectionery that produces decorative bakery products, chocolates and other type of sweets is one of the food industry fields which can benefit of the dimensions that the 3D-printing can offer. However, 3D-printed chocolates and other decorations should not be confused with moulding which has already been developed for long in confectionery sector[817]. The 3D-printed moulds for instance to make cake decorations are widely in use already, like explained by Head of Research of large Finnish confectionery producer Fazer Group. Although some of the confectionery producers are taking the first initial steps in 3D-printing, we already see chocolate printers on the market, like the Choc Creator by Choc Edge from United Kingdom, and American The Hershey Company's CocoJet which is developed in collaboration with leading American printer manufacturer 3D Systems Inc. 3D System'sChefJet™ Pro is also used for printing confectionery.

[816] Mei Lin, winner of Bravo's Top Chef worked with 3D Systems Culinary to 3D-print the passion fruit flavored cloche that tops her colorful dessert. [Photo courtesy of 3D Systems]

[817] Isai, G. (2015) Choc Edge: 3D-printing won't compete with moulding but will boost personalized confectionery market. 30-Apr-2015. Available: http://www.confectionerynews.com/Processing-Packaging/Trends-in-3D-chocolate-printing-The-cans-and-cannots. (accessed 11.12.2015)

In addition to consumer and industry printers, we also see some pioneering consumer service concepts. A UK based confectionery maker, Katjes Fassin Ltd., commercialised the world's first 3D food printer for consumer retail, and opened in August 2015 a concept store in Berlin, called The Magic Candy Factory. Their novel technology ensures decent printing process of fruit gum which enabled them to offer sweets' customisation packaged in fun and educational concept. This technology was developed in collaboration with TNO. In addition to personalised fruit gum candy, the Magic Candy Factory is most of all an experience given that one candy takes relatively long time to print and is costly.

According to van Bommel from TNO (interview), the only area in food where 3D-printing is in large scale use is Dutch pancake industry at the moment. This is considered however not to be pure 3D-printing but shows the potential of 3D-printing technology in the food industry. In turn, Finnish Fazer Group, a confectionery and bakery manufacturer, foresees prospects of 3D-printing in food R&D. Like many other food companies in Europe and elsewhere, also Fazer has at the moment only initial plans to exploit 3D-printing and follows actively how the research and pilots develop in this area. Currently, companies still wait affordable 3D-printers and references to make the investment decision.

It could be said that consumer market for 3D-printed confectionery exists already as consumers are interested in personalised products, but from the industrial engineering and management perspective the exploitation of 3D food printing is not yet feasible. The examples illustrate (Boxes 36-39) the major recent or on-going European research projects in the field of 3D food printing. For instance, the private Edible Growth (Box 37) illustrates an interesting example of the potential of 3D-printing to create fun, healthy and personalised food.

Box 58: PERFORMANCE project

EU funded PERFORMANCE project lead by German food innovation company Biozoon. PERFORMANCE is a EUR 3 million project that developed a novel nutrition concept for the elders suffering from dysphagia – chewing and swallowing difficulties generally resulting for a stroke or dementia. Many of the innovative solutions developed as part of PERFORMANCE including data software for meal details and unique active packaging are now primed for commercialisation (Source: Cordis database). The project is a multidisciplinary collaboration project spanning five European countries. The project research partners are TNO in Netherlands, Danish Technological Institute, Weihenstephan-Triesdorf University of Applied Sciences in Germany, and University of Pisa in Italy. The key company partners are in addition to Biozoon, De Grood Innovations BV and Marfo BV in the Netherlands, FEMTO Engineering in Italy, Sanalogic and Meyer Burger AG in Germany, and Amer Karim nursing homes in Germany. The overall objectives and impact of the project are new processing approaches and tailor-made technologies for the use by small and medium sized (SME) food producers to produce personalised food for the frail elderly European consumer. (http://www.performance-fp7.eu/)

Box 59: The Edible Growth project

The Edible Growth project is a research into sustainable and healthy 3D-printed food. The concept of Edible Growth shows that creating healthy natural and sustainable food is conceivable when combining science, design, technology and food (www.3ders.com). Edible Growth is an individual project of a Dutch food designer Chloé Rutzerveld. Project is implemented in collaboration with TUE (Eindhoven University of Technology) and TNO. The Edible Growth project fits the category "Food for Thought" and is partly created as a form of critical design. The Dutch food designer wants to show that high-tech food or lab-produced food does not have to be unhealthy, unnatural, and not tasteful. Edible Growth shows real growth, an intensifying flavour and structure, makes smart use of natural processes like fermentation and photosynthesis and lowers the use of resources. (http://www.chloerutzerveld.com/#/edible-growth-2014/; Jobson 2015)

Box 60: CIBUS-Food (Computational-design and Innovative Building of Uniquely Structured Food)

The aim of the collaborative project is to investigate 3D-printing technology as a novel, and more sustainable production process for food products. Project concentrates on meat-replacement and bakery products, and focuses on research in the following areas: design and modelling to generate printer files of the 3D structures to be printed, material selection and formulation to meet process requirements, 3D-printing technology selection and process optimization, printed food product characterization methodologies and protocols. The project is led by KU Leuven in Belgium and the other partners are TNO (Netherlands), Weihenstephan-Triesdorf University of applied sciences (Institute for Food Technology) in Germany, Wageningen University, Laboratory of Food Process Engineering in the Netherlands and two companies, namely Biozoon Food Innovations GmbH, Germany and Bruker microCT (formerly known as SkyScan), Belgium. The project runs from 8/2014 to 7/2016 and is funded from A SUSFOOD Era-NET. (http://www.biw.kuleuven.be/biosyst/mebios/cibus-food/cibus)

Box 61: 3DSURPRISE (Multilayer food textures by advanced manufacturing technologies)

VTT Technical Research Centre of Finland Ltd in collaboration with Aalto University and private companies launched one of the first research projects on 3D-food printing in Finland. The project is planned for 2016-2019, and is funded by partners and Finnish Funding Agency for Innovation. The private company participants are from the area of 3D-printing (3DTech Ltd), food manufacturing (Valio Ltd), private R&D (Polttimo), software solutions (Desk Artes Oy) and food services (Selecta Ltd, Ravintolakolmio Oy). The main objective of the 3DSURPRISE project is to develop new applications of advanced manufacturing technologies for 3D-printing of multi-textural food structures in a techno-economically feasible and sustainable way. A specific aim is to create new ingredient mixes with suitable flow properties for 3D processing.

Future application area: personalised 3D-printed food for special groups of consumers

The second case field is 3D-printing in dietary and nutritional food which is very nascent but some experiments in the area exists, like the EU funded project called Performance (see Box 36) and EraNet project CIBUS-Food (Box 38). Performance project was the first to address the issue of producing personalised food for the frail elderly European consumer who wish to eat meals that are presented in a consistency in keeping with traditional meal forms. This is evidently one of the potential areas of personalised food, and fulfils the criteria of niche market in which customisation using 3D-printing could be beneficial (interview with Schutyser). One of the promising fields is to create appetizing, nutritious, and easy-to-swallow 3D-printed meals for the elderly who suffer for instance conditions such as strokes, dementia, or Parkinson's. For these elderly chewing or swallowing can be painful or difficult, leading to the risk of choking, food ending up in the lungs, or malnutrition. Another important reason for developing 'senior food' is taste given that many elderly may suffer from lowered sense of taste.

Another potential category is 3D-printed food using alternative ingredients and materials to create healthy and tasty food. Given that food printers have already been on available for a while, different materials for 3D-printing are continuously tested mainly in the research organisations. The European leading research organisation in the field, TNO, concentrates to create novel food structures, and searches possibilities to alternative base materials to enrich the food, like proteins from insects or algae (TNO 2015). The 3D food printing can help transform alternative ingredients like proteins, that are otherwise hard to process into tasty products with appealing structures that are good not only for health but also for the environment (TNO 2015).

A third category of personalised food is people suffering from different illnesses; therefore have special dietary requirements. Elderly are not the only special group of consumers who might enjoy 3D-printed tasty food but many illnesses may cause lowered sense of taste or lack of appetite permanently or temporarily. For instance, cancer patients often suffer from lack of appetite during their treatment. Especially children patients' loss of appetite may lead to malnutrition. This special group of consumers could benefit of possibilities offered by 3D-printing, although, according to discussion with experts, currently the health care sector professionals perceive this extension to take place in the distant future. This field still need to overcome the prevailing organic and pure food trend before 3D-printing takes off in this field. Many challenges are still to be solved in this field, e.g. how can 3D-printed food be appealing to patients who have lost their sense of taste.

Although the experiments in the dietary food sector are at very initial stage, the size of worldwide market is appealing to food manufacturing companies. To get some perspective of the potential market size, a closest market to this is the medical foods, which is not be confused with dietary supplements, drugs or food with a health claim. Medical foods are instead a special category of disease-specific foods administered to sick patients. Within the medical food market, the US and Europe account for the major share in market revenue (both more than 25 % each) and the global market is estimated to be $13.34 billion in 2018. Given that the medical foods are used for preventive care, a one of the major focus areas of health care in Europe, non-prescription medical foods account for a high share in market revenues. (Balasubramanian 2014) It should be noted that medical foods is a highly regulated area, which do not exactly comply with 3D-printed dietary and nutritional food discussed in this report.

4.2.10.2 Identifying value chain components

(i) Identification of key players and usage of Additive Manufacturing

The value chains in 3D-printed food are currently developing. From the gate-keeper interviews performed, it became evident that identifiable value chains in 3D-printed food are largely non-existent and difficult to identify. Research in the field is led by Dutch TNO who performs the experiments with food companies, and is an active partner in European research projects related to 3D food printing. For this reason, the value chain illustrations depict rather the future potential construction of value chain than the current existing value chain. Like illustrated in Figures 148 and 149 the key actors in the 3D-printed food are public and private R&D actors, who are testing and experimenting in collaboration mainly with small food companies, restaurants and chefs as well as some larger food manufacturers like Barilla (see Box 40).

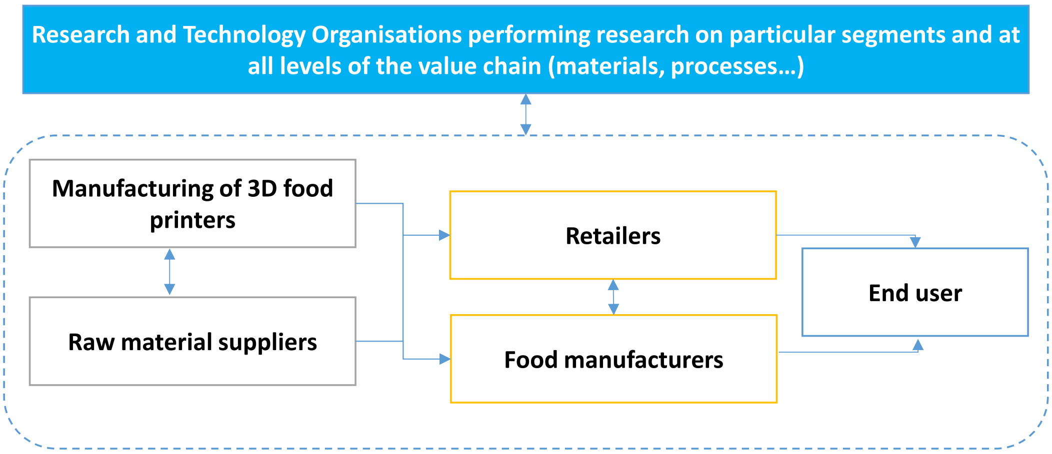
The main challenges for not observing the value chains in commercial use are the lack of viable business models. The large European food producers, like pasta maker Barilla and Marfo from the Netherlands, are exploring the opportunities but the current 3D-printing speed does not offer companies production scalability. For this reason, products that can be 3D-printed are high value premium products (like cake decorations or chocolate) and companies are to innovate new business models often very different from their traditional knowledge and capabilities. European companies are however active in searching solutions and models, and some novel consumer services concepts, e.g. in the confectionery field, have recently been launched.

At the moment, the activities in the 3D food printing are research and experimenting that shows in collaboration between the different actors. Given that different food materials have different requirements for 3D-printing, the actual printer development is largely performed in companies developing different service concepts. Especially RTOs (mainly TNO) are involved in this work as well, given that they have pilot production facilities. Many smaller R&D service focused companies are also developing innovative concepts, such as 3D-printed dinner at pop-up restaurant. The main channels to reach end users and customers are online stores through which 3D-printers for different food ingredients are sold, although also stores and café concepts are increasing. The following section will explore each of the value chain components and actors (research, printer manufacturers, raw material suppliers, service providers and end-users) more in detail and tries to describe the main opportunities and challenges the actors encounter in the 3D food printing, mainly in the confectionery but also more widely in the food sector.

(ii) Composition of the value chain

As mentioned the operating value chains in 3D-printed food in Europe (or elsewhere) are nearly non-existent, given that the area is in the research and experimenting phase. Figures 119 and 120 offer an illustration of the value chain in the 3D food printing field at very general level, and the identified actors have shown potential and interest in 3D food printing and are already experimenting in the field. The main challenge in making the value chains visible in Europe is to attract the food manufacturers, which means that the 3D food printing should be scalable to food production processes. The gate-keeper interviews confirm, that many interesting small scale experiments with RTOs and smaller food ingredient companies are currently running but larger food companies are waiting successful examples from the industry before investing in 3D-printing. Another bottleneck is different printable raw materials and ingredients that research actors are exploring, the raw material development goes hand in hand with printer development as there is not yet a food 3D-printer on market that allows to print multiple food materials.

Figure 148: Main segments of the confectionery additive manufacturing value chain



Research

The most parts of value chain are visible in the research where the leading research institute in the field, TNO, actively co-operates with food companies. The Dutch TNO has developed as the leading research institution in the field because of its knowledge both in food sciences and additive manufacturing, many other European research organisations do not have this combination of knowledge in house. The research focus in TNO is fairly recent as well, as they have only begun to do research in 3D-printed food in the early 2010s. Regardless of the short history, TNO has been able to invest in the 3D-printing technologies and machines and is able to offer companies advice and services in developing and piloting their products. The reasons why research in 3D-printed food has not adopted in many institutions yet is the high price of printers and the knowledge needed for building such food printer. Although the 3D food printers use readily available technological solutions, these printers have to be modified for printing food. According to van Bommel (interview), the greatest competition comes from startup companies but he sees other research organisations to pick up 3D food printing area soon as many organisations are exploring the potential of the field. In-house knowledge and 3D food printers make TNO the leading actor in the field. TNO was unanimously named as the main actor in the gate-keeper interviews.

Another European RTO with similar competencies with TNO, VTT Technical Research Centre of Finland is currently running some experiments in 3D food printing. VTT has developed simple fractionation concepts for production of protein concentrates and antioxidative phenolic extracts from rapeseed oil pressing residue. VTT's approaches in food research are brewer's spent grain and fractions for bread, yogurt and other applications; use of bioprocessed bran as bakery ingredient to deliver high-fibre food rich in protein; concentration of bran proteins for food uses (e.g. performance proteins) and use of oat protein and legumes (fababean) and fractions in bread, pasta and extruded snacks. Some of these could potentially be experimented with 3D-printing. (Poutanen & Nordlund 2015.) At the moment, VTT is though taking initial steps and experimenting different ingredients in 3D food printing (see Box 39).

In European university field, the Belgium University of Leuven (KU Leuven) works in EU funded project (CIBUS-Food, see Box 38) together with TNO, and concentrates mainly on food characterisation side, whereas TNO runs the tests with the 3D food printers. KU Leuven experts are mainly interested in 3D-printed food texture given that their expertise lies in design and computational engineering. Active research partners in European projects have also been Wageningen University in the Netherlands and Weihenstephan-Triesdorf University of Applied Sciences located in Freising, Germany. Many private companies are also contributing to the research and experimentation in the field, often in collaboration with leading research institutions.

Research in Wageningen University in 3D-printing in general started in 2014, the concentration is however more on exploring the potential of technology than in 3D-printing in food in particular. From the student's point of view the topic of 3D-printing is very popular. According to Prof. Schutyser (interview), they are currently exploring the difficulties to use fuse deposition modelling with different materials, and the ingredient functionality to 3D-printing. Wageningen University performs a lot of research in ingredient production and uses 3D-printing as a platform to test functionality of components.

Besides experimenting different raw materials to be 3D-printed, all the research actors are involved in finding nutritious solutions for food which also addresses the needs people with special food requirements. This is clearly one of the major areas research actors are currently involved. In the area of meals tailored to the nutritional needs of individuals, the Nestlé Institute of Health Sciences (NIHS) has launched late 2013 a project on how to meet dietary needs with 3D food printing[818].

Printer manufacturers

The main technologies used in the food 3D-printing are FDM (Fused Deposition Modelling), a technology invented by Stratasys in the 1990s. These printers are modified with syringes and extrusion heads to print food stuff. Another technology commonly used in the food printing is simple inkjet technology. According to van Bommel (interview), current research concentrates in turn on powder based technologies. Although 3D food printing is not yet mainstream, some printer manufacturers who have adjusted their printer technologies to food sector are found. Many food companies are also developing their own 3D-printers.

De Grood Innovations, the Netherlands, is one of the leading 3D-printer developers in food. Their FoodJet 3D food printers have been used for instance in the European PERFORMANCE project (see Box 36) to re-create classic comfort foods, including peas and gnocchi, mimicking their taste, texture, and even incorporating additional nutritional value (Kira 2015). For example, the Dutch pancake manufacturer uses FoodJet technology that is the only industrial scale 3D-printed food example currently. Their technology is labelled as 2D+ printing, not pure 3D-printing.

In the early 2016, Spanish Natural Machines is expected to release their Foodini 3D-printer that is new technology to print fresh personalised food. Printer development has faced some challenges given that commercialisation has been postponed some time already (interview with van Bommel). The printer is aimed mainly to restaurants and private people, and has been used in 3D-printed dinner experiments of Spanish restaurants like Dos Cielos and La Boscana.

A startup, Print2Taste-Bocusini from Germany, develops a 3D food printer that allows users an easy to use to, plug & play model. Project is funded by Kickstarter and printer is expected to be released soon, at the time of writing company was running the final tests. Bocusini is able to print for instance marzipan. This printer is aimed to consumer market.

In the confectionery sector you find some specialised printers as well. One of oldest ones is the UK based Choc Edge Ltd. who developed the world's first commercially available 3D chocolate printer which has been available on the market since 2012. The technology is a spin out from University of Exeter in southern UK (Jia et al. 2016). Some experiments have also been made in the Imperial College London by students who have utilized and modified existing 3D-printing technology to construct the F3D-printer capable of printing a recognizable meal, a pizza[819].

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[818] Molitch-Hou, M. (2014) Nestle Wants to Meet Dietary Needs with 3D Food Printing, 24 June 2014. Available: http://3dprintingindustry.com/2014/06/24/nestle-wants-meet-dietary-needs-3d-food-printing/ (accessed 15.12.2015)

[819] Alec (2014) The F3D 3D-printer doesn't just print pizza, but also cooks it in less than 20 minutes. August 29, 2014. Source: http://www.3ders.org/articles/20140829-f3d-3d-printer-makes-pizza-in-less-than-20-minutes.html (accessed 15.12.2015)

A third British example originates from Cambridge University and the company is called Dovetailed Ltd. Their novel 3D-printer, nūfood, is able to make edible structure from liquid. The printer combines individual liquid droplets with different flavours into a desired shape of fruit.

An Italian 3Drag FDM 3D-printer is capable of working with for instance with chocolate paste. This brings food printing closer to households as with some adjustments you can potentially turn any 3D-printer to print also food. However, experiments are still on-going and issues, such as the melting phase and tempering temperature, are important to be solved in any food 3D-printing.

As non-European examples could be mentioned, the PancakeBot, also a kickstarter project that is the first 3D food printer for personalised pancakes. The production has started in December 2015 in US and Canada. In addition, the US based 3DSystems Inc. has developed the CocoJet, a chocolate 3D-printer, in collaboration with the North American largest chocolate manufacturer, The Hershey Company. This machine is for professional use at the moment, but as the printer works with open-source patterns so it is possible to upload your own design too[820]. Users can choose between dark, milk or white chocolate which all have slightly different consistency for printing.

Raw material suppliers

Although many suitable food materials exists for 3D-printing, not all food and ingredients are suited since material needs to have certain viscosity. For example, the biggest challenge for Choc Edge in developing the 3D technology was to find the right type of chocolate that would layer itself up (Frost & Sullivan 2014).

More futuristic experiments are also reported for fabrication in 3D-printing. A US start-up Modern Meadow has created artificial raw meat in bioprinter that is an ecological alternative for meat[821]. Bioprinting of live cells is though highly more complex compared to some of raw materials such as chocolate or doughs. This process of bioprinting resembles to biomaterials used in printing artificial organs for transplants, for instance.

There can be special and strict preconditions to food ingredients related to 3D-printing. Ingredients must be flowable to extrude from the nozzle. Ingredients also must hold its structure to maintain shape after depositing on the printing platform. Understanding of glass transition, gelation, rheology and melting properties of the material will be significant. Also, the inherent characteristics of various ingredients, heat resistance and cooking properties of the printed material need to be taken into account. In addition, material's biochemical and microbiological properties and biological variation should also be considered[822].

Some foods, such as cake frosting, processed cheese, hummus and chocolate are natively printable. These are extrudable through a syringe tip and hold their shape under gravity. The mixture of sugars, starch, and mashed potato are also natively printable and they were tested as powder materials in Z Corporation powder/binder 3D-printer (since 2012 ZCorp. was acquired by 3D Systems). However, none of them is the main course of meals. Some traditional foods were tested for printability study using Fabaroni (a homemade 3D-printer made in MIT). Judging by the printing viscosity, product consistency, and solidifying properties, the most successful material was pasta dough. Food products made by natively printable materials can be fully customized for taste, nutritional value, and texture. Some of the natively printable materials are stable enough to hold the shape after deposition and do not require further post processing. (Sun et al. 2015)

Other foods, such as fruits, vegetables and meats are in turn not natively printable. In order to be able to print these significant food types, considerable reformulation efforts have to be undertaken. These types of challenges have already been tackled by molecular gastronomists. In this avant-garde culinary field, it is becoming typical to make solids (e.g., meats) extrudable by adding hydrocolloids. With the appropriate molecular gastronomic tricks, it is possible to realize both printable solid foods and printable semi-solid liquids, and the possibilities are practically limitless. (Cohen et al. 2009)

Alternative ingredients in food products might be one of the solutions dealing with the global crisis of food shortage. In the "Insects Au Gratin" project, insect powders were mixed with extrudable icing and soft cheese to shape food structures and make tasty pieces with 3D-printing[823]. When compared with traditional meat products, the protein concentration in insect powder, an alternative source for protein intake, is a little higher. Food printing can greatly contribute to make unpleasant aesthetics and cultural background of insects more appealing to consumers. (Sun et al. 2015.)

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[820] Brick, J. (2015) A collaboration between 3D systems and Hersheys upgrades DIY chocolate. 12 January 2015. Available: http://www.psfk.com/2015/01/vinyl-cover-music-dj-qbert.html (accessed 29.1.2016)

[821] Moskvitch, K. (2013) Modern Meadow aims to print raw meat using bioprinter. BBC News, 21 January 2013. Available: http://www.bbc.com/news/technology-20972018 (accessed 15.12.2015)

[822] Yang, F., Zhang, M. & Bhandari, B. (2015) Recent Development in 3D Food Printing, Critical Reviews in Food Science and Nutrition. Available: http://www.tandfonline.com/doi/pdf/10.1080/10408398.2015.1094732 (accessed 17.12.2015)

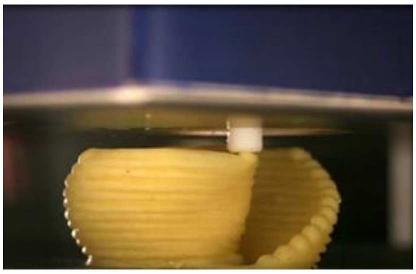
[823] Soares, S. (2011) Insects au gratin. Available: http://www.susanasoares.com/index.php?id=79 (accessed 17.12.2015)

Box 62: Barilla 3D-printed pasta shapes

In 2015 was introduced a world first prototype pasta printer which is co-developed by Italian Barilla and TNO. The printer is capable of printing four elements every two minutes. The pasta dough is traditional, just durum wheat semolina and water without any additives. Barilla and TNO collaboration started in 2013, and a year after Barilla launched the Print Eat contest for designer to design an innovative pasta shape. This contest was won by rose shape pasta that blooms in boiling water that illustrates well the unique features the 3D-printing can offer.[824]

Retailers

The expectations of 3D-printed food are to revolutionise the food consumption so that personalised meals are made at exactly the right moment in home or in a restaurant which can lead to flexible decentralised (local) production (TNO, 2015). The potential service providers in the 3D-printed food value chain are for instance restaurants, cafes and specialised shops (like Magic Candy Factory in Berlin), and grocery shops in which one could offer 3D-printing services. At the moment, 3D-printed food products (and printers) are mainly offered via web stores.



We find some experiments in the fine dining sector, in which restaurants have served or are developing 3D-printed dinners. It seems that particularly in Barcelona area, we find courageous restaurants as two of our examples come from there. The fine dining sector is potential contributor of the finesse 3D-printing can offer. So far, 3D-printed food has been experimented in Dos Cielos restaurant in 2014 with Foodini printer and La Boscana[825]. Also pop-up fine dining concepts have been tested in Europe and the US. A digital gastronomy specialist a Spanish Reimagine Food with different partners has developed the fine dining concepts that utilises 3D-printing as much as possible from utensils to food. Given that scalability of 3D-printed food in the fine dining is not even attainable, might the new technology possibly elevate the hand-made gourmet food.[826]

Another example of service concepts is a specialised shop or café that offers 3D-printed products. An Amsterdam based MELT Icepops has offered custom made iceopops since 2012, and uses 3D-printed moulds that are printed with domestic 3D-printer manufacturer Ultimaker's printers. MELT Icepops is currently developing a 3D-printer that can print iced shapes, but this project has proved to be a lot more difficult than originally anticipated[827]. See also The Magic Candy Factory example in section 4.2.10.1 that is one of the latest service concepts in the 3D-printed confectionery.

In the dietary food field, the potential service providers are naturally health care professional, like hospitals or nursing homes. Like discussed earlier in this report, some experiments are found in Europe of which the best known is Performance project that piloted the products in German nursing home for elderly, but mainly this areas is highly underdeveloped. Health care professionals see the 3D-printing in dietary food still far in future. A German Biozoon Food Innovations is developing raw materials and concepts for people with special diets, and concentrates on R&D in the field of gastronomy and new forms of nutrition for specific segments of the population.

Private R&D operators

Given that the concepts for 3D food printing are still largely non-existent, has the field attracted many private research and development firms who operate in the intersection of technology and gastronomy. For example Spanish Reimagine Food operates as digital gastronomy ecosystem developer, and Robots in Gastronomy (RIG) is a research and design group of professionals from different backgrounds who has also launched a food printer called RIG FoodForm 3D. RIG's scientists have experimented to 3D-print ice cream with FoodForm printer. 3dChef is in turn a Dutch based business-to business market focused innovation and development company.

End-users

The consumers can be reached via thee main ways, serving them 3D-printed products in restaurants and cafes, offering them service to print personalised products (incl. on-line shops), or self-printing at home. Generally, the 3D food printers are expected to make their way to private kitchens alongside coffee makers.

In a consumer's home, the food printer brings two key additional abilities, injection of knowledge and automation. Knowledge injection is the transfer of information or skills from one or more people to a user by the use of programing and mechanical systems. The printer can improve the abilities of the users. For example, users would take a countertop device and use it to produce highly accurate shapes of food. Control of a robotic arm can be more precise than a human hand.

[824] Alec, 2015. Source: www.3ders.org

[825] Hue, E. (2015) 3D Food Printing: Is It Ready for Luxury Dining? Forbes, Jul 31 2015. Available: http://www.forbes.com/sites/eustaciahuen/2015/07/31/3d-food-printing-is-it-ready-for-luxury-dining/#36de93a64b62 (accessed 29.1.2016)

[826] Molitch-Hou, M. (2014a) Two 3D-printed Meals Served on Either Side of the World. 8 July 2014. Available: http://3dprintingindustry.com/2014/07/08/two-3d-printed-meals-served-either-side-world/ (accessed 29.01.2016)

[827] Source: https://www.facebook.com/melticepops

Translating a user's design from a computerized drawing to movements of the printer would enhance the skills of the original chef. This would continue the trend of cake decorating devices like the Cricut Cake where users are able to use digital design files to make custom artwork in two dimension out of fondant. (Lipton et al. 2015)

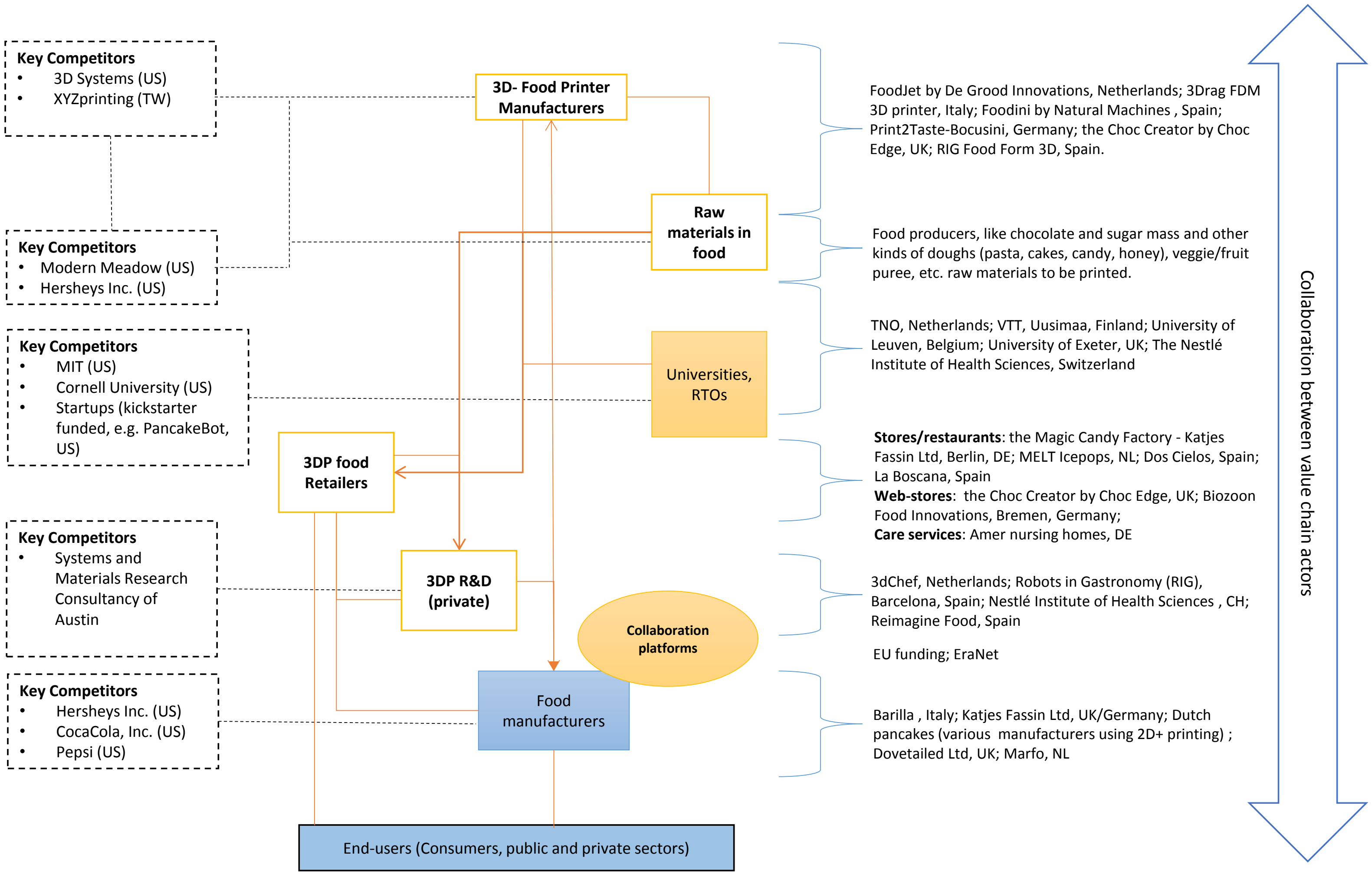
Cohen et al. (2009) write that the 3D food printer can fill in the knowledge gaps of the user by providing a computer driven food production device. A user would select the requisite properties of a dish (flavour profile, texture, etc.) and the machine would convert those requirements into a new recipe for the food. The item would be automatically prepared and ready to be served. Automation would also allow for dietary implementation. A single point of access for food could account for the user's habit and automatically track intake and adjust portioning and content to enforce diets. (Cohen et al. 2009)

Further development in food will require developing more versatile techniques for calibrating the materials for 3D-printing, designing methods for integrating data about the individual, and establishing algorithmic representations of food dishes rather than traditional recipes. These algorithms would need to map the input space of the dish (crispiness, tenderness, flakiness, etc.) to the process parameters of the recipe. Researchers and industry will also have to develop more steady print materials. Most 3D-printed food stock has an extremely limited shelf life. Often the dough used in 3D-printers is only usable for one to two hours after production. Afterwards the rheology tends to shift and the material becomes unsuitable for 3D-printing. (Lipton et al. 2015.)

Gaining the acceptance of medical nutrition professionals might be more difficult to attain, than private consumers buying printers home or testing 3D-printed food in restaurants for fun. In the medical sector, the challenge is that the end users are suffering illnesses and the client of 3D-printed food (e.g. dietarian) is not the end-user to whom the food is offered. It might be challenging to get a patient who for instance because of lowered sense of taste desires no food to adapt to any kind of food. However, like the Performance project has shown there are different consumer groups in the field, like elderly whose food related challenges differ considerably from cancer patient for instance. Another group of end-users for personalised food is foreseen in sports, given that athletes need nutritious often protein rich food. For instance, some extreme sports like ultramarathon runners could potentially benefit of small sized snacks.

A recent study by Jia et al. (2016) explored in simulation study two different business models, manufacturer-dominant and retailer-dominant models, which are also illustrated in the tentative value chain in Figure 149. Their (ibid) case study concentrated on 3D-printing of chocolates and offered additional information for designing supply chains and viable business models in the chocolate manufacturing.

Figure 149: Illustration of the 3D-printed food value chain



Note: the names of the organisations mentioned are only included for illustration purposes and no colour code was applied – colours codes were only added to make the figure more readable.

(iii) Functioning of the value chain and critical factors

The current area of 3D food printing is very nascent and under-developed to detect extensive value-chains. 3D food printers are expensive and allow only limited food stuffs to be printed at the moment. Research focuses mainly on the printing of different types of raw materials to actually offer tasty and nutritious food. Rather than talking about 3D-printed food, we talk about parts of food that can be 3D-printed, like decorations in confectionery sector.

Large food companies are exploring the potential of 3D-printing but struggle with viable business models. Major challenge for companies is to find solutions for scalability but new mind-set requires also to developed to design radical service concepts to reach consumers. Food industry is after all fairly traditional sector where introduction of new market disturbing innovations is slow. The breakthroughs are expected to come from SMEs and new start-ups who are more flexible and willing to take challenges compared to large food manufacturers. According to Verboven (interview), small start-ups are important actors to take the 3D food printing in mainstream. But, at the same time he sees the consumer acceptance as one the main challenges in the field as consumers perception to high-tech and manipulated food is negative given that today’s food trend is strong in natural food products. For instance, the 3D-printing of personalised food according to dietary requirements demands for engaging other than traditional food manufacturers and retailers to the value chain. One example of these is software companies (like a German IT company Sanalogic GmbH who took part in PERFORMANCE project and developed an algorithm) to make sure customer’s diet is well balanced. Creating the future value chains in the area of 3D food printing requires strong collaboration between partners from different areas. This in turn requires acceptance and openness from traditional food manufacturers and retailers to unconventional combinations of knowledge and expertise.

It was also pointed out in the interviews (e.g. Tuomi, van Bommel) that the sector should communicate the value added of 3D-printed food more clearly, it seems that neither the research nor industry has been able to crystallise this aspect fully yet. According to Schutyser (interview), the potential valued added is in wider choice of designing products, e.g. to apply multiple materials. But we could question that is this enough? The scalability of 3D-printing in food is clearly one of the challenge, but the research actors (e.g. interview with Schutyser) perceive potential in niche markets in which the product needs to be customised for certain group of people given that local small scale production is expensive.

European companies and research field (mainly TNO) has positioned itself well, given that many start-up initiatives in 3D food printing technologies have materialised and TNO is one of the leading research institutes worldwide that offers services to companies. Strong knowledge in the field relies in MIT and Cornell University is the US in where 3D food printing research took its first steps. Many companies currently concentrate on bringing printers on market which has led to actual recipe design and development aside that in turn hinders the adoption of 3D-printing in medical nutrition. Potential to apply 3D-printing in medical nutrition is acknowledged widely in Europe as there exists massive demand from different medical fields, e.g. in oncology, but also in sports sciences.

TNO started research in the field in early 2010s, and companies were not at all interested in 3D-printing. In 2015, TNO receives inquiries regularly from food industry to explore and pilot different ingredients to be printed. Very careful estimates by van Bommel in TNO and Prof. Verboven in KU Leuven (interviews) indicate that in next five to 10 years 3D food printing could be more established in some dedicated industries. Also, van Bommel estimates that within couple of years TNO faces heavy research competition from the university sector. We see already new actors approaching this field, like Finnish VTT.

Furthermore, the present and future pressing areas in 3D food printing are food safety and sustainability that all the value chain actors have to address from research field to food manufacturers and service providers. Sustainability is one of the angles integrated in the CIBUS-Food project led by KU Leuven in Belgium.

4.2.10.3 Missing capabilities

(i) Regional dimension and missing capabilities

As mentioned, the 3D food printing value chains are largely non-existent at the moment but some regional hotspots can be detected that shows initial clustering of 3D food printing actors. By looking at the identified actors from the regional perspective, we are able to observe some areas in which initial value chains seems to be developing, although not all needed capabilities from research to retailers serving the consumers are seen in any region yet. One should remember that the existing examples depicted in this report are mostly experiments not established ways of producing or serving food.

- One of the emerging regional areas in the 3D-printing is Barcelona, in Catalonia, in which the activities are centralised to printer developer Natural Machines’ Foodini. In this region some restaurants have been actively involved in experimenting 3D-printing in food, such as Dos Cielos and La Boscana. In addition, Reimagine Food, a digital gastronomy ecosystem developer and Robots in Gastronomy, a research and design group, which operates in the same area. Catalonia area has potential in the retailer (i.e. restaurants) field to act as test ground for the 3D food printing, but for example no RTOs are identified in this region.

- Another identifiable regional ecosystem is in the Netherlands, which is strong in research due to strong university and RTO actors, namely TNO in Eindhoven and Wageningen University in Gerderland. These actors have engaged food manufacturers, like Marfo in Lelystad in Flevoland or smaller explorative startups and private R&D actors such as 3dChef that manufacturers customised confectionery. The multitude of different types of actors and capabilities in the Netherlands, makes the country a potential place to spot emerging value chains. TNO as leading research actor is improving the attractiveness to set up 3D food printing value chains to this region.
- A third nation to mention in tapping the regional value chains is the UK where some initiatives are based on university research which are though little scattered in the country. We find couple of printer developers spinning off from universities, University of Exeter (Choc Edge) and University of Cambridge (nūfood printer) respectively. The UK shows potential in 3D-printing food research and couple of good examples, but does not seem to have established value chains either.
- Fourth region that has some activities related to 3D-printing in food is in Germany, in the Bremen area, in where activities are centralised around Biozoon GmbH. In Germany, the activities not very centralised to any particular region but are scattered from southern Germany (Freising) to northern Berlin, where the first 3D-printing candy store is located.

Given that the overall number of actors in the 3D food printing is a handful in Europe, these actors are connected and collaborate in research projects, but they are rather scattered in Europe still. Main actors are in the Western Europe and Eastern European countries are absent in this new interesting area of AM.

To summarize the critical missing capabilities:

- Because of the scattered and small number of actors, one of the main missing capability in the 3D-printed food in Europe is the lack of specialization. There are not yet specialized areas with accumulated knowledge on specific application areas in the 3D food printing. The main reason is that Europe does not at the moment have volume in the 3D food printing area. Europe lacks actors in all areas, from research to retails, which prevents fully operating clusters and ecosystems to develop. Specialized regional competences are to arise only when there is enough critical mass.

  Current challenge to Europe is to increase the collaboration of scattered actors, and to share technologies and know-how. Fostering collaboration at European level is important in two aspects: including private unprejudiced innovative food technology companies into research projects, and improving knowledge exchange of European research organisations in common projects. Open knowledge sharing in an application area which is in the exploratory phase is fairly restricted.
- The food industry is not only waiting good results from pilot production examples, but the machines and raw materials for industrial use are missing as well. Development and new innovations in these areas are important for manufacturers to adapt 3D-printing in the food production.
- Understanding of feasible business models in 3D-printed food is lacking and would require further emphasis from the industry but also especially from research, like marketing and other business sciences. Adopting 3D printing in consumer markets, like food, paves the way for service innovation.
- In addition, it can be seen that the main activities in the 3D-printing in food are concentrated on few Western European countries, and no clear indication of companies or research actors from Eastern Europe that have engaged in 3D-printed food is available.

(ii) Barriers to the uptake and further deployment of AM in the value chain

The present area remains at a low level of maturity. This explains for example why IPR concerns are not seen as a key barrier. IPR in confectionery and food in general relates mainly to design rights. E.g. in designing a food product such as pasta shape requires acknowledging the designer. Food 3D printing technologies are developed for different ingredients which mean that the food printers, and related technologies, should also be protected with patents. Manufacturing of 3D printed food is largely in a research stage at the moment and commercialising aspect including IPR issues did not receive much weight in the interviews. Current IPR concerns relate to pre-commercial research contracts[828] – but still cannot be put forward as a key barrier to the adoption and deployment of AM in this value chain at this stage.

Adopting 3D-printing for manufacturing and designing food encounters certain challenges whether in households, vending machines, grocery stores, or in space. In order to deploy this novel technology and further AM strategies in food service, there are various limitations concerning food safety, regulation, and availability of ingredients which should be considered to a great extent.

Food production takes place in various different contexts, and different venues such as restaurants and grocery stores may one day host 3D-printers. Thus, it is important to consider how regulatory agencies such as the US Food and Drug Administration (FDA) classify these venues and what influence their regulations will have on production.

[828] However, also printer patents are an important issue given that the 3D food printing technologies are continuously developed for different foodstuffs.

For example, the FDA currently differentiates between locations that "produce" food and those that exclusively sell packaged food. Once a package seller begins interacting with raw, non-packaged food, it may expect to face a novel regulatory regime. Organizations that choose to make this transition will need to consider issues such as cleaning parameters, training of in-store personnel and regular controls. Currently there are no regulations in place for 3D-printed food, so guidelines for specific foods, facility inspections and personnel training will be established without a doubt by FDA. For example restaurants have precise regulations and they need consistent outputs, so they will be taking particular interest in AM guidelines. (Porter, Phipps, Szepkouski & Abidi 2015)

Another consideration for 3D-printed food and especially extruded foods has to do with temperature fluctuations during the extrusion process. By tradition, when material is extruded, it must be heated to create a substance sufficiently malleable to pass through the extrusion nozzle. Such heating and cooling process may represent a health anxiety for food. Heating and/or cooking can make food susceptible to microbial growth, bacteria, or fungus, therefore decreasing its valid shelf life. The prototypes of 3D food printers require careful calibration of multiple parameters, each dependent on the particular batch of food. Different ingredients carry different shelf lives, and packaging can also be one factor. (Porter et al. 2015)

There are also food types that cannot be printed. Unlike other AM applications that extrude only a single material, printing of food often calls for multiple ingredients. These ingredients are ranging from processed components such as sauce, cheese, or dough to more elemental ingredients such as proteins, sugars, and carbohydrates. On account of carrying storage, temperature requirements and chemical compositions, it may be impractical to place these ingredients all in one container. A conceivable option is for the user to manually prepare ingredients at the time of use. Unmanned systems such as vending machines would demand increased levels of automation and regular cleaning. (Porter et al. 2015)

The variety and quality of ingredients are inevitably and for some disappointingly restricted, since creating an organic product, for example a carrot from the outset is still very much in its infancy. For now, to approximate meat, a printer would probably build a consumable protein by mixing a protein powder with water and then shaping the resulting paste into a form that attempts to imitate its natural counterpart. Both home and retail AM users are expected to continue looking for further development with respect to variety in ingredients, among other areas in edible printing (Porter et al. 2015).

3D-printed food production is not excessively low-priced either which create an additional barrier to deployment. The cost of 3D-printed food products includes expenses associated with printing platforms (hardware and software) and printing materials, labor cost, operation cost, and general overhead for maintaining the production facility. The current price of commercial food printing platforms is at the least a few thousand dollars[829] [830], which is too high as a consumer product in terms of fabrication capabilities. In addition, consumers need to purchase printing materials from the platform companies which are more expensive than that of the similar materials in the market. (Sun et al. 2015b)

Another challenge arises in the knowledge sharing which is critical to advance the research and acceptance of 3D-printed food. To enchance the communications between food scientists, food engineers, marketing people, distributors, and consumers during the product development stage, food producers need to explore ingredient combination and elaborate new design samples. However, it is always challenging to find suitable equipment with simple design and reliable performance for a small batch production. An encouraging solution is to further develop the food printer as a prototyping tool to conduct small batch production in a cost-effective and time-efficient way. It can help to fully understand comprehensive technical requirements, explore ingredient combination, taste, and mouthfeel prior to starting mass production. The fabricated food products may be used to verify consumer interest in a proposed design and ingredient stability of specific designs. This may also help filter out a large number of design candidates that do not meet the requirements in a short time at acceptable cost. (Sun et al. 2015b)

Material properties play significant role on the achievement of printability, applicability and resistant constructs upon cooking post-processing. Foreseeing and understanding how the essential constituents of food (carbohydrates, proteins and fat) behave during AM processes bring useful insights into the AM of food structures which will help future research into the optimization of printable multicomponent mixtures. (Godoi et al. 2016)

To summarize the main barriers and challenges to deploy the 3D-printing in food:

Knowledge and know-how

- Little accumulated knowledge yet in the research scene. Only few RTOs and universities in Europe have invested in the 3D-printed food research and technologies.
- Advancements are needed in several areas of the printing and manufacturing technologies, e.g. in temperature fluctuations during the extrusion process.

[829] Choc Creator, http://chocedge.com/ (accessed 15 April 2016)
[830] 3D Systems, 2013. 3D Systems acquires the Sugar Lab. Available at: http://www.3dsystems.com/de/press-releases/3d-systems-acquiressugar-lab (accessed 15 April 2016)

End-user acceptance

- Present organic & healthy eating trend prevents users to adopt 3D-printed food. Health conscious consumers avoid additives which are often required for the proper structure of printable food mass.
- Cost of 3D-printed food is high that makes it unaffordable for many consumers.
- Food safety, especially of synthetic food, is a great concern for many end-users.
- The price of 3D-printed products can create mismatch with consumer's expectations and producers.

Regulation

- Currently there are no regulations in place for the 3D-printed food which prevents the food manufacturers to engage in 3D-printing in large scale.
- Lack of regulation also affects the food safety, such as hygiene of food printers.
- Lack of regulation (like packaging marking) affects the acceptance and image of 3D-printed food.

Ingredients

- Not all food ingredients are applicable for 3D-printing, experimenting and printer development takes time.
- In order to advance in the 3D-printed food, the technologies to extrude multiple ingredients are needed.

4.2.10.4 Conclusion: opportunities for public support

Given that 3D-printing in the food sector is still in very early stage and critical mass is lacking, the main opportunities for policies are found in the awareness raising and capability development in all levels of the value chain. The following points could be seen as more general recommendations for adapting 3D-printing in many nascent application areas. In addition, we observe some more specific points related to the food sector that relate to the safety and IPR that are also great concerns in many other application areas as well. Based on the observations in this report, the main policy implications to foster value chain operations in 3D-printed food are formulated:

(1) Enhancing the image of 3D-printing to improve the acceptance of 3D-printing as (manufacturing) method in the food sector. This encompasses the dissemination of relevant and targeted information of the 3D-printing and adapting the 3D-printing as broader concept than a mere manufacturing method. Communication should be addressed to all value chain actors, targeting specifically the industry and consumers to improve knowledge of the 3D printing in food sector, including technologies and potential business models. Promoting R&D by setting up targeted research calls and incentives to the stagnated food industry would encourage companies to innovate more. For instance, 3D-printing could be integrated in design of products, to earlier stages of product development. Especially in food sector that has a slightly dubious attitude toward 3D-printing, awareness raising campaigns could be beneficial to engage different value chain actors to experiment and pilot 3D-printing. One way could be to involve European Fab Labs (Digital Fabrication Laboratories) to be used as test beds for food printing.

(2) Ensuring the availability of skills is certainly an important factor for 3D-printing to take off in future. This requires integration of 3D-printing in education curricula in several areas of food sciences, food processing technologies etc. However, the feasible business models need also further understanding as adopting 3D printing in food is likely to change consumer behavior. This relates to the point raised earlier that 3D-printing should be seen as broader concept than mere manufacturing method. The development of business models should firmly be included in the European research agenda of 3D printing. For instance, ideas (e.g. to minimize food waste) could be adopted from the circular economy. Commission could promote and coordinate actions related to integrating 3D printing technology and business development. The 3D printing in food would benefit of European level research projects that integrate technology and business development. Understanding of consumer behavior is essential in this context.

(3) Addressing issues related to product safety are important for policy-making especially in the 3D-printed food. Here it is also recommended not to focus purely on 3D-printing as new manufacturing process but to adopt a broader perspective. In food sector product safety relates to serving and distributing food, and issues such as labelling and marking of 3D-printed food packages. Awareness raising would help to prevent 3D-printed food to receive a negative image, like gene manipulation has had. IPR raise concern in many areas of the 3D printing, in some extent also in the food sector. Here, the main concerns are in design rights of food but they depend largely on how the 3D-printed food is served. For instance, the food can be designed by a chef in restaurant, a consumer on the spot, e.g. in the confectionery store, or a confectionery store can use some ready-made designs, e.g. an Eiffel Tower. Food sector may also organise design competitions for different food products, like pasta that credits the winning designer. In addition to design rights, the food printers, and different technologies and software related to the printing of food, benefit from IPR like any other technology fields.

(4) There is also a clear need for the orchestration of research in the 3D-printed food at the European level to prevent the possible overlap in the research. Launching research calls at the European level that would create collaboration projects among European actors are beneficial to increase the knowledge and technology sharing among the scattered research institutes and companies currently working, or aiming to work in the area of 3D-printed food. Designing research calls that include innovative private companies and public research actors is important. Setting up shared facilities and platforms of 3D food printing at the current exploratory phase should be encouraged. This would also potentially lead to the development of stronger regional ecosystems.

Annexes

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2/ Sectors-Applications Matrix (SAM)

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Aerospace	**Structural parts for aeroplanes, especially engines (e.g. turbine blades, fuel nozzles)**	1-2	First components approved for commercial jet engines	EBM, SLM, DED	General Electric (GE Aviation / Morris Technologies), SNECMA, Hamilton Sundstrand, Boeing, Honeywell International Inc., Lockheed Martin,... CFM International (joint venture of GE & Snecma), Amaero (Australia)	AvioAero by GE Aviation (Turin/Milan), Rolls Royce, BAE Systems, Snecma (FR) ...	Airbus and its suppliers, Graphite Additive Manufacturing (UK), Avio (Italy), Arcam (Sweden)	B-to-B	Reduced costs, shorter lead time, reduced inventory costs, better performance, better quality, reduced buy-to-fly ratio	Special metal powders. Advanced materials.	Growing	Energy savings and emission reductions	Varetti, M.; Recent Achievement in Additive Manufacturing at Avio Aero. Additive Manufacturing for Defence and Airspace Europe Conference. 18.-19.2.2015, Lontoo. Slides, 16 p. http://www.fda.gov/downloads/MedicalDevices/NewsEvents/WorkshopsConferences/UCM418401.pdf 2.4.2015, http://www.merlin-project.eu/home/index.jsp, http://www.gizmag.com/ge-faa-3d-printing-aircraft-engine-part/37018
Aerospace	**Non-structural parts for aeroplanes (e.g. electrical**	1-2	Have been used in military many years and increasing usage in	SLS, FDM, Material Jetting, SLM	Boeing, Stratasys, McDonnell Douglas	Airbus, Strasys europe	Airbus and its suppliers	B-to-B	Reduced costs, shorter lead time, reduced inventor	Advanced materials.	Growing	Energy savings and emission reductions	http://3dprintingindustry.com/2015/05/06/airbus-a350-xwb-takes-off-with-over-1000-3d-printed-parts/

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
	boxes, brackets, air ducts)		commercial side						y costs, better performance, better quality, reduced buy-to-fly ratio				
Aerospace	**Components for satellites (e.g. multifunction casing, RF filters, optical baseplate, bracket)**	1-2	Prototyping parts and various flight ready parts.	SLM, SLS	Lockheed Martin Space Systems, Boeing	ESA consortium	ESA coordinating actions with its suppliers	B-to-B	Reduction of cost, mass, lead time, and complexity of assemblies, high performance materials	E.g. carbon nanotube reinforced polymer (CNRP)	Growing	Energy, and material savings.	Williamson, M., Building a rocket? Press "P" for print... Engineering and Technology, March 2015, p. 40 - 43, ESA Roadmap, http://www.flightglobal.com/news/articles/lockheed-martin-reveals-f-35-to-feature-nanocomposite-357223/

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Aerospace	**Component repairing, based on directed energy deposition and hybrid technologies (e.g. aircraft engine compressor components, blisks (intergrally bladed rotors), airfoils)**	1-2	Demonstrations	DED	Sciaky, Optomec, Lockheed Martin, ...	Trumpf-Sisma, Fraunhofer ILT, Hermle (Germany), Wojskowe Zakłady Lotnicze Nr 2 (Polish aircraft repair company), UK Space Agency, Airbus...	E.g. Rolls-Royce Deutschland, Fraunhofer ILT; Zortrax, Poland (3D-printer manufacturer)	B-to-B	Cost and time savings, maintanence, security	Combination of materials possible	Growing	Material savings.	Nannan Guo et al, Additive manufacturing: technology, applications and research needs, Front. Mech. Eng. 2013, 8(3), 215-243. http://www.us.trumpf.com/nc/en/press/press-releases/press-release/rec-uid/267872.html..html, http://www.ilt.fraunhofer.de/en/publication-and-press/brochures/brochure_Repair_and_Functionalization.html
Aerospace	**Components for very demanding environments (e.g. hypersonic flight**	2-3	Under research	E.g. Binder Jetting (FEF)	USA (e.g. Missouri S&T for ultra high temperature ceramics)	ESA consortium	Does not exist.	B-to-B	Demanding environments, complex structures	E.g. ultra high temperature ceramics, refractory metals etc.	Growing	Development of material science	Nannan Guo et al, Additive manufacturing: technology, applications and research needs, Front. Mech. Eng. 2013, 8(3), 215-243.

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
	systems, rocket propulsion systems)												
Aerospace	**Fabrication of spare parts and satellites in spacecrafts and spacestations**	2-3	First componets have been printed	FDM, etc.	NASA consortium and ESA consortium	ESA consortium	Does not exist.	B-to-B	Avoiding launching from the earth	Depends on the application	Growing	Space utilization	http://3dprint.com/88514/made-in-space-and-nanoracks-sign-deal-to-build-and-deploy-cubesats-in-orbit/
Automotive	**Jigs and assembly tools (e.g. for in bodyshell construction, painting)**	1-2	Commonly used	SLS, FDM, SLM etc.	all leading manufacturers	e.g. Volvo, BMW, Audi	e.g. Volvo with Stratasys, Audi with Materialise	B-to-B	productivity, flexibility	tool steels	Tooling can have moderate impact		Günter Schmid and Ulrich Eidenschink, BMW Regensburg: WITH FDM IN JIG & FIXTURE CONSTRUCTION. Stratasys White paper.
Automotive	**Prototyping for product development (e.g. visual models,**	1	Broadly used	various	all leading manufacturers	BMW, Audi (Lamborgini), Volvo, Fiat Chrysler,..		B-to-B	Faster product development, better performance,		Prototyping can have only limited impact		3D-printing from Stratasys and Energy Group Help Lamborghini Make Cars Faster. Davide Sher By Davide Sher On Tue, May 5, 2015

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
	functional models for wind tunnel testing)								avoiding mistakes				
Automotive	**Personalized car interiors (e.g. dashboard) and exteriors (e.g. wing mirrors and other non-sturctural components)**	1-2	At BMW, more than 100,000 parts a year are being made additively, according to Wolfgang Thiele, more than 95 percent of those are polymer-based interior and functional parts.	FDM etc.	e.g. BMW. Several Chinese companies (e.g. Shanghai Dragon Automot Technol Co Ltd) have wide patent portfolio	BMW, Ai Design (customized car manufacturer); Italy: Ferrari, Lamborghini, Agusta, Ducati; Mercedes,	e.g. BMW using stratasys technology, EOS, Additive manuf. Services: CRP Group, Skorpion, Energy Group and Proto Service	B-to-C	personalization, mass customization		Growing		https://www.stratasysdirect.com/case-studies/automotive-personalization-brought-to-life/

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Automotive	**Demanding components (e.g. gear box, powertrain parts, water pump wheel)**	1-3	Under research / testing, e.g. in race cars, first parts approaching to commercial vehicles	SLM, SLS	e.g. BMW	BMW, Germany; Prodrive (UK); Fiat Chrysler Automobiles (FCA);	Michelin joint venture with Fives (metallic AM), France	B-to-C	better performance, complex structures		Growing, large and broad supply chain across Europe		Allen Kreemer, Stratasys, Inc. Motor Trends - Additive manufacturing drives production of race-ready parts. AM SRA. Wohlers 2015 - applications. http://www.metal-am.com/news/003245.html
Automotive	**Printed car body, chassis**	2-3			Local Motors (China)			B-to-C		e.g. CFRP, foams			https://localmotors.com/3d-printed-car/, http://www.techtimes.com/articles/67341/20150709/local-motors-unveils-the-design-of-highway-ready-3d-printed-car.htm
Automotive	**Light commercial vehicles (e.g. light weight parts, personalized parts)**	2-3	Toyota's highly customized i-Road Personal Mobility Vehicle, market launch 2016		Toyota (Japan), Jim Kor's Urbee (US)			B-to-C	Customization, personalization, light weighting			Energy savings and emission reductions	http://3dprintingindustry.com/2015/07/06/rinkak-provides-toyota-with-mass-3d-printing-for-i-road-project/

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Healthcare	**Inert implants, hard implants i.e. bone replacement (e.g. acetabular implants, skull implants, sternum implants)**	1-2	More than 90 000 acetabular implants have been produced by AM, about half of them implanted. Some skull implants (polymer based) implanted succesfully. First sternum implant has been succesfully implanted (2015)		e.g. Oxford Performance Materials (US)	e.g. Symbios (UK), joimax (German), Layerwise (part of 3D Systems), Belgium, Nanotec Marin GmbH (Germany), Stanmore Implants Worldwide, 3T RPD Ltd, Implantcast GmbH, 3Dceram	WASP (Italy); Materialise (Belgium); Arcam AB (Sweden),	B-to-B, B-to-C	product customization and personalization, structural optimization (e.g. gradient structures), independence of economies of scale	Bio-compatible / bio-absorbable materials. Purity of materials	Growing, very innovate industry is emerging		Wohlers 2015. http://3dprintingindustry.com/2015/07/10/the-first-3d-printed-sternum-implant-deemed-a-success/, http://www.nanotecmarin.de/index.php/en/technologies
Healthcare	**Tools, instruments & parts for medical devices (i.e. tools and jigs for**	1-2	Major manufacturing technology for hearing aids, other areas growing		Many US hearing aid manufacturers e.g. GN ReSound , 3D Systems, Medical Modeling,	Siemens, Lima Corporate (Italy), GN ReSound (Denmark), EnvisionTEC Germany, DSM	LayerWise, Belgium (advanced direct metal 3D-printing	B-to-B, B-to-C	more efficient production chain, mass personalization, remote	Bio-compatible materials	Growing		http://www.forbes.com/sites/rakeshsharma/2013/07/08/the-3d-printing-revolution-you-have-not-heard-about/

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
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	surgery, i.e. Kelly hemostat, needle driver, tissue forceps, retractor, scalpel handle and Metzenbaum scissors) (eventually also consider exoskeletons)		or under research				and manufacturing services);Materialise (Belgium); EOS, Germany; Ruetschi Technology AG (Switzerland), Concept Laser GmbH (Germany), Envision TEC with GN ReSound		operations				

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Healthcare	**Dental (e.g. crowns, braces and dentures), also dental devices**	1-2	3D-printed dental guides. Indirect production of dental crowns	SLM, SLS	e.g. Align Technologies Inc (Invisalign Dental braces), DENTCA (USA), Stratasys (Israel/USA)	3DMedicalPrint, Austria; SLM Solutions Germany; EOS Germany; Concepts Laser Germany; Planmeca Group, Finland, Mat Dent NV, Implant & 3D Planning Ctr, Skyscan NV	Roboze, Bari Italy (High precision printer manufacturer)	B-to-B, B-to-C	Mass personalization, more effient prodution	Bio-compatible / bio-absorbable materials. Purity of materials	Growing, strong impacts		Economist: 3D-printing scales up, http://3dprintingindustry.com/2015/08/10/dentures-get-3d-printed-boost-with-dentcas-fda-approval/, http://www.3ders.org/articles/20140524-uk-dental-lab-plans-use-3d-printing-to-create-custom-made-spinal-implants.html
Healthcare	**Medical aids, supportive guides and prosthesis (e.g. facial prostheses, arm prosthesis)**	1-2	At least facial prosthesis manufactured commercially, others coming		Fripp design, UK (facial prosthetics)	e.g. Materialis, various DIY projects with service suppliers	Materialise	B-to-B, B-to-C	Mass personalization, more effient prodution	soft materials			Oliver Wainwright: Faces to order: how 3D-printing is revolutionising prosthetics. http://www.theguardian.com/artanddesign/architecture-design-blog/2013/nov/08/faces-3d-printing-prosthetics

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Healthcare	**Prototyping i.e. preoperative models (prototypes based on scanning data)**	1	Increasingly used. From technological perspecive, the challenges are more related to scanning and other detection technologies, not to printing itself.		Various players	Various players e.g. Materialise, 3D Systems, Blueprinter	Materialise, Blueprinter	B-to-B, B-to-C	service, education, avoiding mistakes		Prototyping can have only limited impact		http://www.news-medical.net/news/20150803/3D-printed-models-of-childrens-brain-anatomy-help-reduce-operative-risk-of-complex-procedures.aspx

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Healthcare	**bioprinting, organ printing (e.g. human skin, blood vessels, kidney)**	2-3	Under research. Two-dimensional producs (like skin) will be first applications, followed by hollow tubes (blood vessels etc.) then hollow organs and finally solid organs. Scaffold is on approac, and might also been 3D printed.		e.g. Organovo (US), Wake Forest Institute of Regenerative Medicine (US), 3D biotek (US), Advanced biomatrix (US), TeVido BioDevices (US) several universities e.g. Wake Forest School of Medicine	regenHU Ltd (Switzerland), L´Oreal (France)	L´Oreal (France) with Organovo (US)	currently B-to-B, in future maybe B-to-C	personalization, productivity				e.g. Murphy and Atala – 3D bioprinting of tissues and organs, http://edition.cnn.com/2014/04/03/tech/innovation/3-d-printing-human-organs/, https://agenda.weforum.org/2014/08/3d-bioprinting-changing-medicine/, http://labiotech.eu/loreal-get-into-bio-printing-skin-for-cosmetic-tests/, http://www.technavio.com/blog/top-10-3d-bioprinting-companies, http://tevidobiodevices.com/

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
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Healthcare	**smart medicine (e.g. personalized dosage)**	1-2	First FDA approval for 3D-printed prescription drug (Aprecia, US). Under research		e.g. Aprecia, US			B-to-B, B-to-C	personalization, productivity				http://3dprintingindustry.com/2015/08/03/fda-approves-the-first-3d-printed-drug/
Machinery & Tooling	**Metallic mould inserts for injection moulding and die casting**	1	Commercially used, but not widely.	SLM, hybrid machines	Marketed strongly by Stratasys.	Major companies in different end-user sectors, e.g. automotive, consumer, aerospace, medical. Volvo Trucks (Lyon FR)	Some supplies exist, like Fado in Poland; Additive Industries (NL); Mcor, Ireland; EOS, Germany, Invision TEC, Germany	B to B	High productivity and high quality through optimal cooling	New tool steels.	Growing, strong impacts on the value chain across Europe	Depends on application.	http://www.stratasys.com/solutions/additive-manufacturing

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
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Machinery & Tooling	**Plastic mould inserts for injection moulding. Short series and prototypes for testing.**	1	Commercially used, but not widely.	Material jetting, SLS	Marketed strongly by Stratasys.	Major companies in different end-user sectors	Lot of suppliers.	B to B	Cutting costs and time.	Heat and wear resistant plastics.	Prototyping can have only limited impact	Depends on application.	http://www.stratasys.com/solutions/additive-manufacturing
Machinery & Tooling	**Sheet metal tools**	1	Commercially used, but not widely.	SLM. For short series and prototyping FDM, Material Jetting, SLS	Marketed strongly by Stratasys.	Major companies in different end-user sectors	Very often in house.	B to B	Cutting time.	New tool steels. Wear resistant plastics.	Tooling can have moderate impact	Depends on application.	https://www.stratasysdirect.com/blog/fdm-sheet-metal-forming/
Machinery & Tooling	**Fixtures and jigs for assembly and welding**	1	Commercially used.	FDM, Material Jetting	Marketed strongly by Stratasys.	Major companies in different end-user sectors, e.g. in car industry.	Very often in house.	B to B	Cutting costs and time.	Cost and time cutting.	Tooling can have moderate impact	Depends on application.	http://www.stratasys.com/solutions/additive-manufacturing, http://www.stratasys.com/resources/case-studies/automotive/bmw

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		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Machinery & Tooling	**Sand moulds and cores for foundries when individual castings are needed. Plastics patterns for sand casting.**	1	Commercially used by early adapter	Binder Jetting, FDM for pattern.	For sand moulds and cores: ExOne, headquarters in the USA. Stratasys active in marketing pattern making. Several players in US	For sand moulds and cores Voxeljet in Germany; Sand Made, Poland, Newbyfoundries, UK, 3Dealise Ltd UK	ExOne (The development ment and production facility in Augsburg, Germany)and Voxeljet supply services. Also other suppliers. Foundries. Several application industries.	B to B	Cutting time, reducing fixed costs, short series	Binders for moulds and cores	Growing, large and diverse supply chain acoss Europe	Depends on application.	http://www.stratasys.com/solutions/additive-manufacturing
Machinery & Tooling	**Patterns for investment casting for short series and**	1	Commercially used.	Material Jetting, FDM	Marketed strongly by Stratasys.	Voxeljet in Germany strong in wax printers.	Often in house.	B to B	Cutting time.	PMMA, wax, SLA		Depends on application.	http://3dprintingindustry.com/2014/03/26/voxeljet-wax-investment-casting-process-3d-printing/, http://www.stratasys.com/solutions/a

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
	product development.												dditive-manufacturing
Machinery & Tooling	**Spare parts for machines (e.g. gears, housings, buttons, fasteners)**	1-2	Cases exist, not in wide use yet (i.e. not provided as servive by OEM's)	Depends on application.	A wide sector: depends on application.	A wide sector: depends on application. Maersk, DK (Fabricate Spare Parts on Ships), online suppliers like Shapeways, iMaterialize and other AM service providers	A wide sector: depends on application.	(B to C), B to B	Cutting time, service business opportunites, bound capital	A wide sector: depends on application.	Growing	A wide sector: depends on application.	
Machinery & Tooling	**Prototyping in product development of machines**	1	Traditional technology	Depends on application.	A wide sector: depends on application.	A wide sector: depends on application. Various service providers	A wide sector: depends on application.	B to B	Cutting time.	A wide sector: depends on application.	Prototyping can have only limited impact	A wide sector: depends on application.	
Machinery & Tooling	**New innovative machine**	1-2	Cases exist	Depends on application.	A wide sector: depends on application.	A wide sector: depends on application.	Supply chain difficult to	B to B	A wide sector: depends on	A wide sector: depends on application.	Growing	A wide sector: depends on	http://www.3ders.org/articles/20150720-automatas-low-cost-3d-

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	s, and components, like low-cost robot arm, heat exchanges etc.						discern due to various end uses		application. Often higher performance.			application.	printed-eva-arm-hopes-to-bring-robotics-to-the-masses.html, http://www.makepartsfast.com/2015/02/7912/creating-multi-metal-custom-heat-exchangers-3d-printing/
Electronics & Electronic Devices	**Printing and embedding electronics for various devices. (e.g. batteries, 3D antennas, sensors)**	2	Prototyping, research stage	Direct Write, FDM, SLA, multi3D systems	USA, e.g. Voxel8, University of Texas at El Paso, Graphene 3D Lab. , Optomec, nScrypt	E.g. Friedrich-Alexander-University Erlangen-Nuremberg, Germany, Bayerisches Lasercentrum GmbH, Germany, Manchester Metropolitan University, the UK,…	does not exist yet, emerging	B to B	Customised products	Conductive inks and filaments	Growing	E.g. clean energy through new battery solutions.	Espalin, D. et al., 3D-printing multifunctionality: structures with electronics. Int. J. Adv. Manuf Technol (214)72, p. 963-978. http://3dprintingindustry.com/2015/07/24/voxel8-ceo-jennifer-lewis-on-how-12m-in-funding-will-fuel-the-future-of-electronics-3d-printing/, http://www.graphene3dlab.com/s/technology.asp, http://www.wired.co.uk/news/archive/2015-

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													08/10/graphene-3d-printed-super-batteries, Hoerber, J. et al., Approaches for additive manufacturing of 3D electronic applications. Procedia CIRP 17(214) p. 806 - 811, Nielse, B. et; Laser Sintering of Silver Ink for Generation of Embedded Electronic Circuits in Stereolithography Parts. Lasers in Manufacturing Conference 2015.
Electronics & Electronic Devices	**Cooling systems (e.g. Integration of cooling channels, high-performance heat sinks)**	2	Research	SLM		Thales	does not exist yet, emerging	B to B	High-performance electronics	High conductive materials	Growing	New solutions.	Thales

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Electronics & Electronic Devices	**Micro-electronics**	2	Prototyping	E.g. two photon polymerisation	Nanosccribe, Germany, AlpZhi, USA,…	Nanoscribe, Germany	does not exist yet, emerging	B to B	Microdevices	Photosensitive materials	Growing	New solutions.	http://www.alpzhi.com/#!, http://www.nanoscribe.de/en/technology/additive-manufacturing/
Consumer life style & fashion (inluding textiles and creative industries)	**Home decoration (incl. Lightning) (e.g. furniture, lightning, small statues, vases)**	1	Commercial	various technologies	e.g. Freedom of Creation (part of 3D systems) Neitherlands, LUXeXcel, Netherlands, .MGX (the design division of Materialise N.V.), Belgium	e.g. Freedom of Creation (part of 3D systems) Netherlands; LUXeXcel, Netherlands; Raybender, Denmark; KIORO design, Italy	e.g. various players with Materialize	b-to-c	Design freedom		Growing		http://www.freedomofcreation.com/collection/products
Consumer life style & fashion (inluding textiles and creative industries)	**Toys (e.g. figures, avatars, dolls, special building blocks)**	1	commecial	FDM	Insanitoy Inc. Mark Trageser (toy designer), US	e.g. Makielab (UK), Launzer (Finland), Lego, many others	Lego	b-to-c	series of one				https://mymakie.com/, https://www.launzer.com/ etc.

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		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Consumer life style & fashion (inluding textiles and creative industries)	**Textiles, cloths (e.g. shoes, bikinis, garments)**	1-2	Some experiments, e.g. haute couture garments since early 2010s. Gradually evolving. Fabric printers are developed.	SLS, FDM, PolyJet	US: Nervous System (a design studio), designers (e.g. Bradley Rothenberg), Footprint Footwear, the United Nude, Sols; US printer providers for textiles: 3D Systems Inc (Fabricate application). Israel also strong in design of clothes with 3D-printing elements.	NL: Iris van Herpen (fashion designer), ACryx (shoe brand); UK: Tamicare Ltd. (3D textile technology), BioKnit (shoe brand)	Luxexcel, NL (printer provider) optics, Philips, Adidas (GE), Grabher (AT)	b-to-c	Offering perfectly tailored clothing. Yet, haute couture is still hand-made intensive.	current: polymers, polymer composites, Abs, PLA, Flexible PLA, Polyamide, Multi-materials with different hardness shore value	Growing		Yap & Yeong: Additive manufacturing of fashion and jewellery products: a mini review, many others
Consumer life style & fashion (inluding textiles and creative industries)	**Smart textiles (e.g. sport textiles, protective textiles, smart helmets)**	2-3	Under research (as 3D-printed). Cases based on other technologies exist.	Material jetting, material extrution			IR: Ouro_botics (augmented tissue); SE: Chalmers University of	b-to-c	better performance		Growing		

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							Technology (3D-printing in cellulose); FI: Aalto University & VTT , AT: Grabher Group						
Consumer life style & fashion (inluding textiles and creative industries)	**Sport / Leisure (e.g. rackets, bikes, sporting shoes)**	1-2	E.g. sport shoes by Nike etc.		e.g. Nike (with Stratasys)	service providers		b-to-c	Improved performance				
Consumer life style & fashion (inluding textiles and creative industries)	**Music instruments (e.g. violins, guitars, panpipes, flutes)**	1	Many showcases. No commercialized products / no business cases / a few instruments sold (e.g. by Diegel)					b-to-c					Olaf Diegel etc.

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Consumer life style & fashion (inluding textiles and creative industries)	**Jewellery (e.g. selective laser melting of precious metals like gold and silver, plastic jewellery, casted jewellery)**	1-2		SLM, EBM, SLA, Binder Jetting (ExOne M-Print, M-Flex), DLP (EnvisionTEC Perfactory), SLS	US: American Pearl Inc. (customers make their own design online, company produces 3D-printed wax mould); SG: Polychemy,	IT: Nemesi (online 3D-printing service for jewellery), KIORO design (design studio); NL(Eindhoven)/US: Shapeways (web based service), Dyvsign Delft; UK: Cooksongold, Future Factories - Designer Lionel T Dean, Weston Beamor,FI: Kalevala koru	IR: Mcor Technologies (paper based 3D-printers for jewellery); Heimerle + Meule Group (refiner and processor of precious metals), Swarovski	b-to-c	Customisation and personalization. Shorter supply chain. Quicker product development.		Growing	3D-printing is changing the economics of the jewellery design market drastically.	Yap & Yeong: Additive manufacturing of fashion and jewellery products: a mini review
Gas & Oil	**Oil & Gas**								Speed of continuing operations can be more important than				

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									the cost of the components				
Gas & Oil	**Prototyping (e.g. PIGs, valves, pump components)**	2	Printed PIG mock-ups accelerate production of actual PIGs		GE (oil and gas division)			B-to-B	Production efficiency, complex structures, customization		Prototyping can have only limited impact		Sikich – 3-D printing..
Gas & Oil	**Demanding parts (e.g. metal nozzles for gas turbines, electric submersible pump)**	2	piloting in 2014, expected production in 2015		GE (oil and gas division)	Siemens oil, gas and marine business		B-to-B	complex structures, better performance, maintanence support security, remote environments				Reuters – Oil industry
Gas & Oil	**Parts for drilling**	2			Halliburton			B-to-B					

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Energy	**Gas turbines: prototyping, repairing, direct manufacturing**	1	In commercial use	SLM, DED	Siemens, Mikro Systems, Inc. (US) subcontractor of Siemens	Siemens, Alstom (FR), Material Solutions Ltd (UK)	Siemens, Materials Solutions Limited (UK), Safran Group (FR), Alstom (FR)	B to B	Time saving, more energy-efficient solutions.	New metal powders.	Growing, rather narrow and specific supply chain acrros Europe	Material saving, more efficient energy production.	http://www.siemens.fi/pool/cc/events/elp14/esitykset/navrotsky.pdf, http://3dprintingindustry.com/2015/08/26/siemens-gas-turbines-to-get-a-boost-via-uk-metal-3d-printing-company/
Energy	**Solar panels and cells (e.g. optimized shape)**	2-3	Under research	Direct Write, Material Jetting,…	Several players starting the game around the world	Research groups e.g. in Holland	Does not exist	B to B	Saving in manufacturing costs. Efficiency, local manufacturing.	Printing on cheap materials.	Growing	Green energy.	L. van Dijk et al., Solar Energy Materials&Solar Cells 139(2015)1920 – 26, http://www.energydigital.com/greentech/3793/Could-3D-Printing-Utterly-Change-Solar-Panel-Technology, http://www.theguardian.com/environment/blog/2013/feb/22/3d-printing-solar-energy-industry
Energy	**Wind power, hydro power, nucler**	2-3	Under research	Depends on the application	Different research groups around the world	E.g. an European project, led by Nuclear AMRC in the	Does not exist	B to B	Depends on the application.	Depends on the application.		Green energy.	G. Scotti et al., Laser Additive Manufacturing of Stainless Steel Micro Fuel Cells,

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
	power, fusion power, fuel cells,...					UK, going on in AM for nuclear components; AT: Tegra Gmbh and Grabher-Group are producing textile electrodes for fuell cells							Journal of Power Sources 272 (2014) 356-361; M. Takagi et al, 3D-prined Pelton turbine: how to produce effective technology linked with global knowledge. Energy Procedia 61 (2014) 1593 – 1596; V. Queral, 3D-printed fusion component concepts and validation for the UST.2 stellarator, Journal of Physics: Conference Series 591 (2015) 012015; http://www.materialstoday.com/metal-industry/news/uk-nuclear-industry-investigates-pm-techniques/

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Construction	**Affodable houses (based on automatisa-tion, redundancy of formworks)**	2	under research / demonstration	Exstrution type printing	WinSun (China), RMIT Institute of Technology (Australia), University of Southern California, Zhuoda Group (China), entrepreneur Lewis Yakich (3D-printed homes in Philippines)	Fimatec (Finland), DUS Architects (NL); Dshape - Monolite Ltd (UK)	IT: WASP (World Advanced Saving Project) creation of the world's largest Delta 3D-printer. AT: Lukas Lang Building Technologies and REHAU AG		Costs		Growing, large supply chains are affected across Europe		Perrot et. al. (France)
Construction	**On-the-spot emergency shelters**	2	under research / demonstration	Exstrution type printing	WinSun (China)	University of Nantes (France) in conjunction with CAPACITES SAS			Time				University of Nantes

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Construction	**Architectural flexibility (e.g. pillars, shape of house)**	2	under research / demonstration	Exstrution type printing	DUS architects (3D-print Canal House), Neitherlands				Esteтhics (time and cost)				
Construction	**Printed bridges and other similar applications**	2	under research / demonstration	DED type printing									Skanska (t&), Nottingham/Lougborough

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Military	**Spare parts (mobile factories, fighters, printers on ships,..)**	1-2	Testing, first cases.		US Army, Chinese Army,	British Army	E.g. BAE Systems and RAF	B to B	Logistics. Quality and speed of maintenance. Money savings.	Depends on the application	Growing	The technology developed can be used also in civilian applications.	http://www.3ders.org/articles/20140105-uk-tornado-fighter-jets-fly-with-3d-printed-parts-for-the-first-time.html, http://www.wired.co.uk/news/archive/2015-02/09/mod-future-of-army-technology, http://www.usni.org/magazines/proceedings/2013-04/print-me-cruiser, http://uk.businessinsider.com/afp-how-3d-printing-could-revolutionise-war-and-foreign-policy-2015-1?r=US#ixzz3eXum1HW5
Military	**Temporary housing**	2	Testing		US Army	Does not exist	Does not exist		Shelters in remote areas	Concrete, etc.	Growing	Also for humanitarian operations and disaster relief.	Horowitz. M.C. (2014) Coming next in military tech. Bulletin of the atomic Scientists. Vol. 70(1), pp. 54-62.

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Military	**Field hospitals**	2-3	Testing		US Army	Does not exist	Does not exist.		Fast treatment on spot of demand (printing implants, healing burn wounds, ...)	Depends on the application	Growing	Also for civilians.	http://www.3dprinterworld.com/article/wake-forest-3d-prints-skin-cells-burn-wounds, http://qz.com/145237/3-ways-3-d-printing-could-revolutionize-healthcare-2/
Military	**Personalized dashboard and controls**	2	under research / demonstration				Have not been recognised						
Military	**special equipments**	2	under research / demonstration				Have not been recognised						http://www.wired.com/2013/04/3d-printed-navy/
Military	**spare parts**	2	under research / demonstration				Have not been recognised						http://3dprintingindustry.com/2015/07/08/3d-printing-sought-to-improve-spare-parts-manufacturing-for-marine-industry/, http://gcaptain.com/printing-change-world/#.VdXSke8w9aQ

Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Military	**Engine parts**	3	under research / demonstration				Have not been recognised						
Military	**customized cabins**	2	under research / demonstration				Have not been recognised						
Food industry	**Personalized food - shape (chocolate printer)**	1	First commercial applications available (e.g. chocolate printer etc.)	Mainly exstrution type printing	3D systems	e.g. Biozoon	Have not been recognised		customization and personalization				many sources
Food industry	**Food for remote locations (e.g. food in space, food in battlefield)**	3	under research	Mainly exstrution type printing	NASA, US army		Have not been recognised		remote operations				http://www.sciencedaily.com/releases/2015/07/150713144118.htm

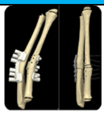
Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
Food industry	**Personalized food - incredients, structure, flavour (e.g. personalized diet, improved flavour by improved stucture)**	2	demonstration and first commercial use	Mainly exstrution type printing	3D Systems (US) produces food printers	e.g. Biozoon, Print2Taste Bocusini (Germany), TNO (Research) Neitherlands, the Foodini by Natural Machines (ES), Nestle (CH) , the Choc Creator by Choc Edge (UK), MELT icepops (NL), The Magic Candy Factory (DE)	3D Ventures (UK);		personalization, mass customization		Growing, has an impact also on many small firms		http://3dprintingindustry.com/2015/04/24/print2taste-emerges-with-the-bocusini-food-3d-printer/, http://www.thewire.com/technology/2014/05/3d-printed-food-actually-looks-and-tastes-pretty-delicious/371863/
Entertainment Industry	**Movies**	1	Used for creating special effects in movies, costume design, etc. Animation		e.g.: Legacy Effects (Hollywood special effects studio), US	UK (animation)		b-to-b	Lower costs and faster processes (e.g. in prototyping).				TNO projects

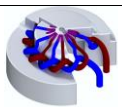
Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
			s. Broadly in use.										
Entertainment Industry	**Games - 3D CAD and 3D file manipulation software**					Materialise, Altair, etc.							https://i.materialise.com/
Optics	**Led lights**	2	Used in LED lighting industry mainly	stereolithography (SLA), multi-jet modeling (MJM) and PolyJet (from Stratasys, Eden Prairie, Minn.)	Formlabs, a 3D-printer company in Somerville, Mass., developed a unique way to polish their 3D-printed lenses.	LUXeXcel, Netherlands	Philips, OSRAM in cooperation with LuXeXcel	b-to-b		Poly(methyl methacrylate) (PMMA) a transparent thermoplastic, Optical liquid silicone rubber (LSR)	extend to consumer market spectaculars, 3D-printed "light pipes" that enable construction of unique display surfaces, novel illumination techniques, custom		

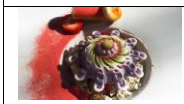
Sector	3DP-Application	Technology			Geographical concentration		European supply chain		Potential			Socio-economic impacts	Source
		Maturity	*Technology readiness*	*Main AM-technologies*	*Global key playes*	*Key European players*	*Network*	*Type of market*	*Business drivers*	*Material development*	*Market expectation*		
											optical sensors and embedded optoelectronic components.		
Optics	**fiber optic cables**												http://3dprintingindustry.com/2015/08/20/breakthrough-glass-3d-printing-platform-unveiled-by-neri-oxman-mit/?utm_source=3D+Printing+Industry+Update&utm_medium=email&utm_campaign=cfd636340c-RSS_EMAIL_CAMPAIGN&utm_term=0_695d5c73dc-cfd636340c-64521293
Optics	**lightning**												

Source: IDEA Consult, AIT and VTT, 2015

3/ Overview of the policy implications derived from each case study

Application Area	Emerging and future AM areas per value chain
	**Surgical Planning:** ▶ Improving (multidisciplinary) skills (on material properties and development, IT, building operation, maintaining AM machines, supply chain and project management) via education and training at the member states level. ▶ Support to further research and development is required in order to overcome certain limitations at the level of the models themselves. In order to improve their accuracy and fidelity (for instance overcoming the simple geometrical reproduction and make possible the reproduction of surgery conditions, reactions and effects), R&D could be supported by all levels of government to further characterize the processes and materials at stake. ▶ There is still room for a broader uptake of AM in hospitals. This involves collaboration efforts at all levels. (a) There is an opportunity to strengthen the relations between healthcare professionals (surgeons), healthcare and AM providers in order to facilitate the uptake of AM in hospitals. One of the prerequisite to such collaborations would be that they take place in a multi-disciplinary context. Collaborations could be set up through projects supported at the regional, national and European projects, which could range from collaborative to capacity building projects. (b) Closely related to the above policy implication, is the need for awareness raising. One of the key challenges is here the one of streamlined information. This could be taken up by European authorities. In this respect, it is interesting to encourage networks and to identify pioneers and champions, which facilities the knowledge and information sharing. ▶ In addition, there is the economic aspect which is also highly relevant for the hospital and patient; who pays for the cost of training and preoperative planning? There are quiet some differences across Europe. Does the individual itself pay for it, the individual's insurance or the national health provider? More clarity and uniformity at the national and European level would certainly benefit the uptake of AM in healthcare.
	**Plastic-based car interior components:** ▶ "R&D support at all levels of government to: ◆ Strengthen the qualification of materials and processes manufacturing; ◆ Develop size possibilities and application of biomimicry concepts ; ◆ Support the development of hybrid manufacturing; ◆ Support composite materials R&D; ◆ Support parts optimization and integration; ◆ Develop multi-material and multi-colour printing; ◆ Strengthen CAD and Software capabilities. ▶ Co-investment from governments at all levels of government, for instance through voucher schemes or collaborative R&D co-funding. ▶ Awareness rising at the EU (and even EC) level, for instance through a one-stop website and dedicated events. ▶ Stimulate demand, for instance through regulation or other policy instruments. ▶ Upgrade EU workforce's skills and update relevant curricula, with the coordination of such consultative process taking place at the EU level.
	**Metallic structural parts for airplane:** ▶ Foster the access to critical materials (titanium, aluminum, magnesium) by strengthening European transformative capabilities. Examples include technology efficiency (R&D) support and setting up relevant networked infrastructures (pilot production, demonstration,,,). "Co-invest in R&D areas such as: ◆ AM processes; ◆ Quality of Material Feedstock; ◆ Material properties; ◆ Quality monitoring, control and detection systems; ◆ Toxicity, explosivity and broader health impacts of nano-sized powders; ◆ High-performance and high-volume production through AM systems; ◆ Large metal components production through accurate AM systems; ◆ When questioned about possible developments that would benefit the area, several interviewees referred to multi-material and hybrid forms of manufacturing. ▶ Collaborative R&D projects, tax reduction schemes and other financial schemes could play this role," ▶ Development of testing, finishing, post-treatment and demonstration capabilities, whether in the context of cross-regional projects or networked infrastructures. ▶ Co-develop new curricula

	▸ Foster standardization ▸ Set up a common repository that could take the form of a one-stop website ▸ Foster cross-value chain collaboration, for instance through application-driven collaborative research (such as in the field of titanium-based structural components, wire-based printing for vehicles, etc.). ▸ Raise awareness through appropriate and targeted events ▸ Support pilot production and demonstration activities in the field of arc and wire-based AM technologies ▸ Stimulate demand, for instance by mobilising existing instruments such as regulation.
	**Inert and hard implants:** ▸ Streamlining of the certification process should be offered by national entities in collaboration with the European Commission services to make sure a certain harmony is found across Member States ▸ The existence of digital designs becomes a potential issue requiring futher enforcement of the IPR system at Member State level and EU level ▸ Improving (multidisciplinary) skills (on material properties and development, IT, building operation, maintaining AM machines, supply chain and project management) via education and training at the member states level (with coordination at the EU-level). ▸ R&D support to be able to overcome the missing capabilities and invest in the future and emerging areas. This could take place in the context of joint research and innovation projects at all government levels. ▸ Raise awareness at the level of users and streamling available information at EU, national, regional and local level. Relevant target groups are doctors, patients, health insurance and government institutions.
	**Metal AM for injection molding:** ▸ Improve access for SMEs to technology organisations, for example through innovation vouchers "Foster the adoption of AM by investing in demonstration activities and: ◆ Compensate for the high cost of printers, for instance with innovation vouchers; ◆ Inform and change the culture of small companies (for instance with awareness raising at the EU level, training at regional and national levels for instance). ▸ Strengthen powder transformation capabilities: ◆ Develop access to market intelligence; ◆ Facilitate business development; ◆ Accelerate the qualification/standardization of powder materials. ◆ Focus on materials such as titanium (EU to coordinate/connect relevant players). ◆ Develop urban mining initiatives. ◆ Accelerate qualification through collaborative consultation. ▸ Cross-regional support to demonstration activities (joint initiatives/projects, networks of infrastructures, etc.) and ordering the links between supply&demand, Eastern and Western EU, on key close-to-market development lines ▸ Support collaborative R&D project on issues such as multi-material printing and design software (such as done under H2020) ▸ Support the (R&D) development of hybrid systems ▸ Develop appropriate multi-disciplinary curricula through a coordinated process to take place at the EU level Enforce IPR regimes at EU and national levels ▸ Raise awareness through web-based channels and events among the customer communities
	**Spare parts for machines:** ▸ Collaborative/cross-regional R&D support (through grants, R&D co-funding, collaborative R&D projects, networks of infrastructures, one-stop shops, etc.): ◆ On materials and processes. ◆ On on-demand and localized printing and the combination of additive and subtractive methods (incl. hybrid manufacturing). ◆ Collaborations linking companies from additive and subtractive areas. ▸ Set up and relate pilot production and demonstration facilities across Europe ▸ Raise awareness (website, events)
	**Lighting and other home decoration products:** ▸ Supporting technological advancements and future innovations with specific R&D needs. ▸ Supporting specific regional collaborations: Potential key regions with high concentrations of involved end users and vendors of 3D-printed home decoration products were identified (e.g. Netherlands/Nordrhein-Westfalen, in Italy, South France, and in Spain)

	▶ Supporting user platforms: Regarding the relatively high involvement of European users (see e.g. Fab Labs or 3D Hubs) within 3D-printing platforms, specific opportunities for Europe could be supported financially and with specific actions ▶ Development of testing, finishing, post-treatment and demonstration capabilities. ▶ Creating new curricula on 3D-printing: Generating knowledge and raising awareness on AM process, materials, applications, and actors, especially in Eastern Europe ▶ Supporting prototypes and experiments:
	**3D-printed textiles:** ▶ More R&D is needed: The breakthrough is expected if this obstacle is overcome and in-line processes make direct 3D-printing on textiles possible. ▶ New curricula (regional and national levels are here concerned but the EC could still take a coordination role here) should be developed in order to foster the diffusion of relevant skills among the EU workforce ▶ Platforms and networks for consumer participation should be strengthened a strong driver for the development are users which can pull the development and form a critical mass which finally could facilitate the formation of larger markets ▶ Collaborations should be supported, especially between research institutes and textile industry.
	**Affordable houses:** ▶ National education and training policies should focus on making sure we have people that understand multiple fields such as robotics, software and construction. ▶ National and EU policies should focus on the creation of platforms and ecosystems that can create the value. Very often value is concentrated around a very few firms and it means that one has to foster these platform firms to grow and to create a value based ecosystem. ▶ More ambitious financing programs both at national and European level are a condition for more ambitious research and innovation outcomes. Moreover in national policies attention should be paid to ensuring the access to finance enabling the uptake of new technologies and the coverage of the related initial costs of adoption. ▶ Further attention should be paid to which cooperation models between industry and RTO's are optimal both on European and national levels. Policy makers both on European and national levels should take a position on how to encourage innovative behaviour in the construction sector and on how to discourage harmful conservative mentalities
	**3D-printed confectionery:** ▶ To enhance the image of 3D-printing to improve the acceptance of 3D-printing as (manufacturing) method in the food sector. Promoting 3D printing as broader concept than a mere manufacturing method. Communication should be addressed to all value chain actors, targeting specifically the industry and consumers to improve knowledge of the 3D printing in food sector, including technologies and potential business models. Promoting R&D by setting up targeted research calls and incentives to the stagnated food industry would encourage companies to innovate more. Awareness raising campaigns could be beneficial to engage different value chain actors to experiment and pilot 3D-printing. One way could be to involve European Fab Labs (Digital Fabrication Laboratories) to be used as test beds for food printing. ▶ To ensure the availability of skills for 3D-printing to take off in future, requires integration of 3D-printing in education curricula in several areas of food sciences, food processing technologies,and business sciences. Treating of 3D-printing as broader concept than mere manufacturing method. The development of business models should firmly be included in the European research agenda of 3D printing. For instance, ideas could be adopted from the circular economy. Commision could promote and coordinate actions related to integrating 3D printing technology and business development. The 3D printing in food would benefit of European level research projects that integrate technology and business development. Understanding of consumer behaviour is essential. ▶ To address issues related to product safety in the 3D-printed food are important. In food sector product safety relates to serving and distributing food, and issues such as labelling and marking of 3D-printed food packages. Awareness raising would help to prevent 3D-printed food to receive a negative image, like gene manipulation has had. ▶ To orchestrate the research in the 3D-printed food at the European level to prevent the possible overlap in the research. One option is to launch research calls at the European level that would create collaboration projects among European actors. These would increase the knowledge and technology sharing among the scattered research institutes and companies currently working, or aiming to work in the area of 3D-printed food. In addition, setting up shared facilities and platforms of 3D food printing at the current exploratory phase should be engouraged. This would also potentially lead to the development of stronger regional ecosystems.

4/ Search algorithms for patent analysis

4.1 Search Strategy by (Gridlogics 831)

TAC:((3D OR 3-D OR 3-dimension* OR 3 dimension* OR (three* w2 dimension*) OR desktop* OR additive*) wd2(print* OR fabricat* OR manufactur*))

AND

(IC:(B29C* OR H01L* OR G06F* OR G02B* OR B32B* OR H05K* OR B41J* OR B41M* OR G06T* OR B44C* OR B22F* OR H04L* OR G03F* OR H04N* OR C04B* OR G05B* OR "G03B35" OR A61*) OR

CPC:(B29C* OR H01L* OR G06F* OR G02B* OR B32B* OR H05K* OR B41J* OR B41M* OR G06T* OR H04L* OR B44C* OR B22F* OR G03F* OR H04N* OR C04B* OR G05B* OR A61* OR "G03B35"))

AND NOT

(TACD:(stereoscopic* OR oxidation product* OR streaming interactive OR nanoweb or nano web OR nanofiber* OR nanofibre* OR nano fiber* OR nano fibre* OR nanometer fiber* OR nanometer fibre* OR non halogen OR non-halogen OR ((food* OR feed* OR liquid*) w2 additive*) OR seed culture OR nanometre fiber* OR nanometre fibre* OR antibacteria* OR media access control OR multi-wafer 3D CAM cell OR 3-sigma or three sigma or rheolog* additive* or vibration isolator*))

Timespan: 1990-5th Feb. 2014

4.2 Search Strategy IPO 832

ALL=((additive NEAR manufactur*) OR ((Additive NEAR laser) NEAR manufactur*) OR (additive NEAR fabric*) OR ((Additive NEAR laser) NEAR Fabric*));

ALL=(((3 NEAR D) or 3d or (three NEAR dimension*)) NEAR (Print* OR Fabricat*OR ADJ manufactur*));

ALL=(((free-form OR (Free NEAR form)) NEAR (Manufactur* or fabrica*)) OR EBF3 OR (Rapid NEAR (Prototyp* OR Manufact*)));

ALL=(((Select* NEAR (sinter* OR Laser* OR HEAT*)) NEAR3 (Deposit* OR Sinter*)) OR SHS OR SLS);

ALL=(((laminat* NEAR object*) NEAR (Manufact* OR fabricat*)) OR ((Fus* NEAR Deposit*) NEAR Model*) OR (generativ* NEAR Print*))

The dataset was manually cleaned by omitting irrelevant patent families.

Timespan: 1982-2013

[831] 3D-printing: Technology Insight Report (2014)¸ Gridlogics Technologies Pvt Ltd; http://www.patentinsightpro.com/techreports/0214/Tech%20Insight%20Report%20-%203D%20Printing.pdf

[832] Intellectual Property Office, 3D-printing: A Patent Overview (Newport: Intellectual Property Office; November 2013) https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/312699/informatics-3d-printing.pdf

4.3 Search Strategy AIT833

((TIEN = 3D “3-D” “3-dimension*” "3 dimension*" three +2w dimension* additive desktop) and (TIEN= print* or fabricat* or manufactur*)) OR ((ABEN= 3D “3-D” “3-dimension*” "3 dimension*" three +2w dimension* additive desktop) and (ABEN= print* or fabricat* or manufactur*))

OR ((CLEN = 3D “3-D” “3-dimension*” "3 dimension*" three +2w dimension* additive desktop) and (CLEN= print* or fabricat* or manufactur*)) AND NOT (TIEN = stereoscopic* “oxidation product*” "streaming interactive" nanoweb "nano web" nanofiber* nanofibre* "nano fiber*" "nano fibre*" "nanometer fiber*" "nanometer fibre*" "non halogen" "non-halogen" food* +2w additive* feed* +2w additive* liquid* +2w additive* “seed culture” “nanometre fiber*” “nanometre fibre*” antibacteria* "media access control" "multi-wafer 3D CAM cell" "3-sigma three sigma" "orrheolog* additive*" "vibration isolator*")

AND NOT (ABEN = stereoscopic* oxidation product* "streaming interactive" nanoweb "nano web" nanofiber* stereoscopic* “oxidation product*” "streaming interactive" nanoweb "nano web" nanofiber* nanofibre* "nano fiber*" "nano fibre*" "nanometer fiber*" "nanometer fibre*" "non halogen" "non-halogen" food* +2w additive* feed* +2w additive* liquid* +2w additive* “seed culture” “nanometre fiber*” “nanometre fibre*” antibacteria* "media access control" "multi-wafer 3D CAM cell" "3-sigma three sigma" "orrheolog* additive*" "vibration isolator*")

AND NOT (CLEN = stereoscopic* “oxidation product*” "streaming interactive" nanoweb "nano web" nanofiber* nanofibre* "nano fiber*" "nano fibre*" "nanometer fiber*" "nanometer fibre*" "non halogen" "non-halogen" food* +2w additive* feed* +2w additive* liquid* +2w additive* “seed culture” “nanometre fiber*” “nanometre fibre*” antibacteria* "media access control" "multi-wafer 3D CAM cell" "3-sigma three sigma" "orrheolog* additive*" "vibration isolator*")

AND NOT (DEEN = stereoscopic* “oxidation product*” "streaming interactive" nanoweb "nano web" nanofiber* nanofibre* "nano fiber*" "nano fibre*" "nanometer fiber*" "nanometer fibre*" "non halogen" "non-halogen" food* +2w additive* feed* +2w additive* liquid* +2w additive* “seed culture” “nanometre fiber*” “nanometre fibre*” antibacteria* "media access control" "multi-wafer 3D CAM cell" "3-sigma three sigma" "orrheolog* additive*" "vibration isolator*")

AND (IPC = B29C OR H01L OR G06F OR G02B OR B32B* OR H05K OR B41J OR B41M OR G06T OR B44C OR B22F OR H04L OR G03F OR H04N OR C04B OR G05B OR G03B35 OR A61) AND (PUD = 2014 or 2015)

[833] An analysis of the new patent class B33Y Additive Manufacturing revealed that until end of August 2015 no patent have been published by the EPO so far.

5/ EU projects dealing with 3D-Printing

Project Acronym	Title	Programme Acronym
	Advanced dental implants manufactured by selective laser sintering	INTAS
DIMACS	Direct manufacturing by micro cold spray (DIMACS)	INTAS
	Novel powdered systems available for direct manufacture of metallic and composite metallic/ceramics components by selective laser sintering rapid prototyping technique	INTAS
RAPROMO	Development of rapid prototyping means in mould manufacturing	CRAFT
	Rapid prototyping with high temperature engineering plastics by use of fused deposition modelling(prototyping)	FP4-BRITE/ EURAM 3
	Development of a process for the manufacture of high performance cementless orthopaedic prostheses with a novel cored biomaterial structure	FP4-BRITE/ EURAM 3
	Rapid production of enhanced EDM electrodes by powder based Additive Manufacturing	FP4-BRITE/ EURAM 3
RPTOOL	Rapid production of tooling	FP4-BRITE/ EURAM 3
	Digital Mould Manufacturing	FP4-BRITE/ EURAM 3
TOY SLS	Validation of selective laser sintering (SLS) for the manufacture of prototype moulds in the toy industry	FP4-INNOVATION
	Development of mechanically alloyed powders and laser processing machine for the fabrication of high performance production metal tools	FP4-BRITE/EURAM 3
PHIDIAS	Technology for manufacturing of medical models based on rapid prototyping and medical imaging technique - quality assessment and application development	FP4-BRITE/ EURAM 3
VITAMIN	Virtual Manufacturing And Rapid Prototyping	FP4-INCO
	Rapid prototyping and tooling industrial applications	FP4-BRITE/ EURAM 3
RAPIDSHELLS	Direct selective laser sintering of ceramic investment casting shells for metal prototypes (RAPIDSHELLS)	FP5-GROWTH
	Rapid prototyping of aluminium alloy products by semi-solid extrusion	FP5-GROWTH
	Rapid manufacturing of products by improved 3D-printing	FP5-GROWTH
DIRECTOOL	The direct production of net shaped metal tools for the casting and moulding industry (DIRECTOOL)	FP5-GROWTH
RAMA3DP	Rapid Manufacturing of Products by Improved 3D-printing	FP6-SME
FLEXRAP	Development of an innovative, modular rapid prototyping system for rigid and flexible models (FLEXRAP)	FP6-SME
CELPACT	Cellular Structures for Impact Performance	FP6-AEROSPACE
NOVELSCAFF	Novel Fabrication Techniques to Produce Scaffolds for Tissue Engineering Applications	FP6-MOBILITY
PRINCIPLE	Printing concepts for innovative patterning of low-cost electronics with (sub)micron resolution	FP6-MOBILITY
RAMATI	Rapid manufacturing of titanium implants	FP6-NMP
CUSTOM-FIT	A knowledge-based manufacturing system, established by integrating Rapid Manufacturing, IST and Material Science to improve the Quality of Life of European Citizens through Custom fit Products.	FP6-NMP
METAL-PRINT	The development of a new Flexible Manufacturing technique for Highly Detailed, Custom Made Metallic Products by Metal Inkjet Printing	FP6-SME
RC2	Reduction of Cycle and Cost	FP6-SUSTDEV
CUSTOM-IMD	SME Supply Chain Integration for Enhanced Fully Customisable Medical Implants, using new biomaterials and rapid manufacturing technologies, to enhance the quality of life for EU citizens	FP6-NMP
NAIMO	NAnoscale Integrated processing of self-organizing Multifunctional Organic Materials	FP6-NMP
MALT	Multilaser Additive Layer Manufacturing of Tiles	FP7-JTI
REPAIR	Future RepAIR and Maintenance for Aerospace industry	FP7-TRANSPORT

Project Acronym	Title	Programme Acronym
FLOWMAT	Exploiting Flow and Capillarity in Materials Assembly: Continuum Modelling and Simulation	FP7-PEOPLE
TIALCHARGER	Titanium Aluminide Turbochargers Improved Fuel Economy, Reduced Emissions	FP7-SME
PILOTMANU	Pilot manufacturing line for production of highly innovative materials	FP7-NMP
SIMCHAIN	Development of physically based simulation chain for microstructure evolution and resulting mechanical properties focused on Additive Manufacturing processes	FP7-JTI
EVOBLISS	Technological Evolution of Synergy Between Physicochemical and Living Systems	FP7-ICT
OPTICIAN2020	Flexible and on-demand manufacturing of customised spectacles by close-to-optician production clusters	FP7-NMP
INTRAPID	Innovative inspection techniques for laser powder deposition quality control	FP7-SME
SPHERESCAFF	The Manufacturing of Scaffolds from Novel Coated Microspheres via Additive Manufacturing Techniques for Temporomandibular Joint Tissue Engineering	FP7-PEOPLE
COPYME3D	CopyMe3D: High-Resolution 3D Copying and Printing of Objects	FP7-IDEAS-ERC
FABulous	Future Internet Web-Entrepreneurship for 3D-printing Virtual Fabrication in Europe	FP7-ICT
COMPOLIGHT	CompoLight: rapid manufacturing of lightweight metal components	FP7-NMP
INLADE	Integrated numerical modelling of laser additive processes	FP7-PEOPLE
DIRECTSPARE	Strengthening the industries competitive position by the development of a logistical and technological system for spare parts that is based on on-demand production	FP7-NMP
A-FOOTPRINT	Ankle and foot orthotic personalisation via rapid manufacturing	FP7-NMP
PLASMAS	Printed Logic for Applications of Screen Matrix Activation Systems	FP7-NMP
PRINTCART	Bioprinting of novel hydrogel structures for cartilage tissue engineering	FP7-PEOPLE
INTERAQCT	International Network for the Training of Early stage Researchers on Advanced Quality control by Computed Tomography	FP7-PEOPLE
ARTIVASC 3D	Artificial vascularised scaffolds for 3D-tissue-regeneration	FP7-NMP
DIGINOVA	Innovation for Digital Fabrication	FP7-NMP
3D-HIPMAS	Pilot Factory for 3D High Precision MID Assemblies	FP7-NMP
HIPR	High-Precision micro-forming of complex 3D parts	FP7-NMP
ADDFACTOR	ADvanced Digital technologies and virtual engineering for mini-Factories	FP7-NMP
FABIMED	Fabrication and Functionalisation of BioMedical Microdevices	FP7-NMP
NEXTFACTORY	All-in-one manufacturing platform for system in package and micromechatronic systems	FP7-NMP
RAPIDOS	Rapid Prototyping of Custom-Made Bone-Forming Tissue Engineering Constructs.	FP7-NMP
KARMA	Knowledge Based Process planning and Design for Additive Layer Manufacturing	FP7-SME
SASAM	Support Action for Standardisation in Additive Manufactruring	FP7-NMP
COMBIPAT-TERNING	Combinatorial Patterning of Particles for High Density Peptide Arrays	FP7-IDEAS-ERC
HIRESEBM	High resolution electron beam melting	FP7-SME
RRD4E2	Rational Reactor Design for Enhanced Efficiency in the European Speciality Chemicals Industry	FP7-PEOPLE
ADM-ERA	Reinforcing Additive Manufacturing research cooperation between the Central Metallurgical Research and Development Institute and the European Research Area	FP7-INCO
MULTILAYER	Rolled multi material layered 3D shaping technology	FP7-NMP
VINDOBONA	VINyl photopolymer Development Of BONe replacement Alternatives	FP7-PEOPLE
M&M´S	New Paradigms for MEMS & NEMS Integration	FP7-IDEAS-ERC
HI-MICRO	High Precision Micro Production Technologies	FP7-NMP
FASTEBM	High Productivity Electron Beam Melting Additive Manufacturing Development for the Part Production Systems Market	FP7-SME
IMPLANT DIRECT	Implant Direct	FP7-SME
SHAPEFORGE	ShapeForge: By-Example Synthesis for Fabrication	FP7-IDEAS-ERC
AMAZE	Additive Manufacturing Aiming Towards Zero Waste & Efficient Production of High-Tech Metal Products	FP7-NMP

Project Acronym	Title	Programme Acronym
AMCOR	Additive Manufacturing for Wear and Corrosion Applications	FP7-NMP
AEROBEAM	Direct Manufacturing of stator vanes through electron beam melting	FP7-JTI
OXIGEN	Oxide Dispersion Strengthened Materials for the Additive Manufacture of High Temperature Components in Power Generation	FP7-NMP
HYDROZONES	Bioactivated hierarchical hydrogels as zonal implants for articular cartilage regeneration	FP7-NMP
SMARTLAM	Smart production of Microsystems based on laminated polymer films	FP7-NMP
IRRESISTIBLE	Including Responsible Research and innovation in cutting Edge Science and Inquiry-based Science education to improve Teacher's Ability of Bridging Learning Environments	FP7-SIS
CASSAMOBILE	Flexible Mini-Factory for local and customized production in a container	FP7-NMP
HI-STA-PART	High Strength Aluminium Alloy parts by Selective Laser Melting	FP7-JTI
MANSYS	MANufacturing decision and supply chain management SYStem for Additive Manufacturing	FP7-NMP
NANOMASTER	Graphene based thermoplastic masterbatches for conventional and Additive Manufacturing processes	FP7-NMP
BIO-SCAFFOLDS	Natural inorganic polymers and smart functionalized micro-units applied in customized rapid prototyping of bioactive scaffolds	FP7-NMP
PRINTCART	Bioprinting of novel hydrogel structures for cartilage tissue engineering	FP7-PEOPLE
STELLAR	Selective Tape-Laying for Cost-Effective Manufacturing of Optimised Multi-Material Components	FP7-NMP
AEROSIM	Development of a Selective Laser Melting (SLM) Simulation tool for Aero Engine applications	FP7-JTI
M&M'S+	3D-printer for Silicon MEMS & NEMS	FP7-IDEAS-ERC
D-FOOTPRINT	Personalised insoles via additive manufacture for the prevention of plantar ulceration in diabetes	FP7-PEOPLE
STEPUP	Step up in polymer based RM processes	FP7-NMP
DIGHIRO	Digital Generation of High Resolution Objects	FP7-PEOPLE
PHOCAM	Photopolymer based customized Additive Manufacturing technologies	FP7-NMP
MERLIN	Development of Aero Engine Component Manufacture using Laser Additive Manufacturing	FP7-TRANSPORT
FACTORY-IN-A-DAY	Factory-in-a-day	FP7-NMP
PP-MIPS	An innovative phosphorus rich intumescent oligomer enabling commercially competitive high performance halogen free fire protection of polypropylene.	FP7-SME
IC2	Intelligent and Customized Tooling	FP7-NMP
SARAFun	Smart Assembly Robot with Advanced FUNctionalities	ICT-2014-1
DiDIY	Digital Do It Yourself	ICT-2014-1
ToMax	Toolless Manufacturing of Complex Structures	FoF-2014
FoFAM	Industrial and regional valorization of FoF Additive Manufacturing Projects	FoF-2014
BOREALIS	Borealis – the 3A energy class Flexible Machine for the new Additive and Subtractive Manufacturing on next generation of complex 3D metal parts.	FoF-2014
Ownerchip	Digital Rights Management Infrastructure For 3D-printed Artifacts	SMEINST-1-2014
NEXT-3D	Next generation of 3D multifunctional materials and coatings for biomedical applications	MSCA-RISE-2014
DISTRO	Distributed 3D Object Design	MSCA-ITN-2014

Source: EUPRO database, CORDIS database, own calculation

6/ Organisations with most participation in EU projects – Summary of projects

Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung

AMAZE (**Additive Manufacturing A**iming Towards **Z**ero Waste & **E**fficient Production of High-Tech Metal Products)

- The goal of AMAZE is to produce large defect-free additively-manufactured metallic components (up to 2 meters) with close to zero waste (50% cost reduction for finished parts) used in the high-tech sectors aeronautics, space, automotive, nuclear fusion and tooling.
- The commercial use of adaptronics, in-situ sensing, process feedback, novel post-processing and clean-rooms in AM will be reduced (quality levels are improved, build-rates increased by factor 10, dimensional accuracy increased by 25% and scrap-rates slashed to 5%)
- The links between alloy composition, powder/wire production, additive processing, micro-structural evolution, defect formation and the final properties of metallic AM parts will be examined

ARTIVASC 3D (**Arti**ficial **vas**cularised scaffolds for **3D**-tissue-regeneration)

- ArtiVasc 3D will provide a micro- and nano-scale based manufacturing and functionalisation technology for the generation of fully vascularised bioartificial tissue that enables entire nutrition and metabolism.
- The bioartificial vascularised skin (engineered in ArtiVasc 3D) will allow tissue replacement with optimum properties. Vascularised skin will also be used as an innovative in vitro skin equivalent for pharmaceutical, cosmetics or chemical substance testing, which represents a promising method to reduce expensive, ethically disputed animal testing.
- ArtiVasc 3D will develop a combination of hi-tech engineering (micro-scale printing, nano-scale multiphoton polymerisation and electro-spinning) with biological research on biochemical surface modification and complex cell culture.

BOREALIS (the 3A energy class Flexible Machine for the new Additive and Subtractive Manufacturing on next generation of complex 3D metal parts)

- Borealis project presents an advanced concept of machine for powder deposition Additive Manufacturing and ablation processes that integrates 5 AM technologies. The machine is characterised by a redundant structures constituted by a large portal and a small PKM enabling the covering of a large range of working cube and a pattern of ejective nozzles and hybrid laser source targeting a deposition rate of 2000cm3/h with 30 sec set-up times. Software infrastructure enables a persistent monitoring and in line adaptation of the process
- Aiming at TRL 6 for two complete Borealis machine in two dimensions – a lab scale machine and a full size machine – which are foreseen to be translated into industrial solution by 2019

CASSAMOBILE (Flexible Mini-Factory for local and customised production in a container)

- CassaMobile develops a mobile, flexible and modular, small-footprint manufacturing system in a 20' ISO-container that can be easily configured for different products and processes which enables the benefits of localised service delivery without duplication of equipment at multiple locations.
- The concept is demonstrated by three use cases (bone drill guides for orthopaedic surgery, medical orthotics and individual industrial gripping products)

COMPOLIGHT (Rapid manufacturing of lightweight metal components)

- The project proposes to solve (by means of experiments, applied research and software development) identified shortcomings of Rapid Manufacturing (RM), namely the lack of design rules, lack of guidelines and simulation software, the possibility of CAD application software to (partly) automate, research in the effective use of RM integrated in a process chain and the lack of ways to define and effectively control surface quality.
- Projected impact from the project originates from a larger industrial utilisation of lightweight components in many industries, including automotive, aerospace, medical, and electronics.

CUSTOM-FIT (A knowledge-based manufacturing system, established by integrating Rapid Manufacturing, IST and Material Science to improve the Quality of Life of European Citizens through Custom fit Products)

- CUSTOM-FIT drastically changes how and where products are designed and made. It creates sustainable, knowledge-based employment, which plays a critical role in safeguarding Europe's manufacturing industry by developing and integrating a completely new and breakthrough manufacturing process based on Rapid Manufacturing (RM)
- Three main technical breakthroughs: Automated design system for knowledge based design of Custom-Fit products, Processing of graded structures of different material compositions and Rapid Manufacturing for Instant and On-Demand manufacturing of graded Custom-Fit products.
- Enables a vertical integration in the value chain and horizontal integration by the ability to transfer the knowledge to other industrial sectors.

CUSTOM-IMD (SME Supply Chain Integration for Enhanced Fully Customisable Medical Implants, using new biomaterials and rapid manufacturing technologies, to enhance the quality of life for EU citizens)

- Custom-IMD develops new biomaterials for the manufacture of innovative fully customised medical implants using enhanced rapid manufacturing
- Main aims: achieving implant design, manufacture, sterilisation, regulatory approval and delivery to the surgeon within a 48 hour time frame / development of innovative biomaterials / achieve integration of the medically certified e-supply chain management

DIGINOVA (Innovation for Digital Fabrication)

- DIGINOVA will establish the current status across material domains and application domains in Europe in order to identify the most promising technology and business propositions for Digital Fabrication.
- 4 large companies, 7 SMEs and 9 research institutes will identify and connect main stakeholders through the establishment of innovation networks centred on specific business cases to determine the added value and feasible routes to commercialisation.

DIRECTSPARE (Strengthening the industries competitive position by the development of a logistical and technological system for spare parts that is based on on-demand production)

- DirectSpare allows manufacturers to rapidly produce only those spare parts that are required, at a location close to the equipment that needs to be repaired
- Advantages of DirectSpare: increase of competitive position, step to introduce new products is made smaller, cost reduction, waste reduction, manufacturing of small quantities.

FABIMED (Fabrication and Functionalisation of BioMedical Microdevices)

- The aim of FaBiMed proposal is to improve and develop new manufacturing techniques, based on micromoulding, specific for biomedical microdevices (reducing the cost of mass production of diagnosis and therapeutic micro devices)

FACTORY-IN-A-DAY (Factory-in-a-day)

- Aims at improving the competitiveness of European manufacturing SMEs by removing installation time and installation cost for robot automation - will reduce the installation time (and the related cost) from months to one single day!
- The project is driven by Europe’s top robotics researchers (e.g. TUD, KUL, TUM, Fraunhofer) and industry players (Philips, Universal Robotics, Siemens, Materialise)

HIPR (High-Precision micro-forming of complex 3D parts)

- Primary goal of HiPr is to develop and integrate all necessary base technologies which create the basis to control and monitor the condition of micro-tooling for complex high-precision 3D parts (in-depth process and material knowledge, in-line measurements, real-time predictive maintenance)
- HiPr helps in assuring a competitive and sustainable European manufacturing industry (reduction of: - cost by >20%; - material and energy consumption by >30%; - development cost reduction >30%)

IC2 (Intelligent and Customized Tooling)

- IC2 will combine state-of-the-art additive and subtractive processes into a hybrid manufacturing cell (precision and performance of high-speed milling - with the geometrical freedom of Additive Manufacturing Technology)
- The results of IC2 is a new concept for Knowledge Intensive Tooling for the benefit of European competitive manufacturing (reduced time-to-marked, process tact times and tooling/manufacturing costs, enables new business models with full tool life cycle service and enhanced high value tools).

INTERAQCT (International Network for the Training of Early stage Researchers on Advanced Quality control by Computed Tomography)

- The INTERAQCT project will develop procedures for fast and accurate Computed Tomography (CT) model acquisition, with special emphasis on multi-material parts.
- By bringing together expertise from industry and academia in the domains (CT-equipment, CT-software, NDT, dimensional metrology, Additive Manufacturing, micro-manufacturing, composite manufacturing) an innovation breakthrough in the EU industry is generated.

LIGHT-ROLLS (High-throughput production platform for the manufacture of light emitting components)

- Light-Rolls focus on research and development of modular based production units for the seamless, high throughput manufacture of micro-structured, polymer based components and Microsystems. The manufacturing modules will be integrable, exchangeable, with mechanical, fluidic and IT interfaces
- The scientific objective aims to realise structures in the micron range and integrate also Dies, smaller then 0,5mmx0,5mm and thickness down to 50 um to be assembled in high-speed.
- For future products a Light-Rolls knowledge base for design for manufacturing will be elaborated.

MERLIN (Development of Aero Engine Component Manufacture using Laser Additive Manufacturing)

- The MERLIN reduces the environmental impact of air transport using Additive Manufacturing (AM) techniques in the manufacture of civil aero engines (near 100% material utilisation, no toxic chemical usage and no tooling costs)
- Consortium comprises six world leading aero engine manufacturers, Rolls-Royce is the coordinator, six renowned RTD providers and two SME's.

MULTILAYER (Rolled multi material layered 3D shaping technology)

- The objective of the MULTILAYER project is to develop a set of solutions for the large-scale production of micro devices based on the Rolled multi material layered 3D shaping technology and using the concept of tape casting and advanced printing techniques.
- Enable to manufacture complex multifunctional 3D-micro parts on a layer by layer manner and in a high-throughput context (Each layer can be given a specific structure)
- Important advantages: efficient mass production / good flexibility for a wide variety possible component designs / integration of different materials as different layers

NEXTFACTORY (All-in-one manufacturing platform for system in package and micromechatronic systems)

- NextFactory project develops and validates a new type of all-in-one manufacturing technology combining 3D freeform printing and ultra-precision 3D assembly in a single piece of equipment.
- Will empower microsystem manufacturers (in particular SMEs) to effectively produce highly miniaturised Smart Products-in-Package (SPiPs) both in small series and high-throughput production of large parallel batches and large variety of products (oral sensors, microsensor chips and complex solar modules)

PLASMAS (Printed Logic for Applications of Screen Matrix Activation Systems)

- PLASMAS directly builds on world-leading nano-materials, printing and display device technologies and directly addresses the current commercialisation barriers by demonstrating the capability of technology through development of printed circuit boards and printed logic.
- Examples are displays with printed copper and silicon-based back panels and established “self-emissive” OLEDs and “reflective” low power Electro-Chromic elements.
- Significant step forward in commercialising these technologies and ensuring that the commercial benefits are maximised for the EU.

Rapid production of enhanced EDM electrodes by powder based Additive Manufacturing

- The aim of this project is to exploit the advantages of Laser and Powder based Additive Manufacture (LPAM) to produce electrodes for EDM and create process chains for this purpose.
- Process chains will include improved RPT processes, post processing and an adapted EDM process optimisation

Rapid prototyping and tooling industrial applications

- The iterative sequence of product development itself is accelerated so that more time is available for product evaluation.
- A stricter planning of procedures and application of simultaneous engineering is necessary - Just in time delivery is the ruling issue.

RAPIDSHELLS (Direct selective laser sintering of ceramic investment casting shells for metal prototypes)

- Four generally laser sinterable ceramic powders, one possible for commercialisation
- Process parameter combinations for ceramic-laser sintering
- Analysis of necessary machine modifications (hardware and software)

SIMCHAIN (Development of physically based simulation chain for microstructure evolution and resulting mechanical properties focused on Additive Manufacturing processes)

- The aim of the project is to establish a full software set, which allows the prediction of resulting mechanical properties of materials produced by Additive Manufacturing processes as a function of process parameters.
- SIMCHAIN is an innovative and unique approach to build a ready to use software set in order to predict the influence of various process parameters on the resulting mechanical properties during Additive Manufacturing processes. It prepares the ground for robust process design, as an important step towards design-driven manufacturing for future aero engines parts optimised in weight and function.

SMARTLAM (Smart production of Microsystems based on laminated polymer films)

- SMARTLAM offers solutions for the gap between a high volume production with specialised equipment and a not efficient production of medium series
- Solutions build on a modular, flexible, scalable 3D-Integration, where novel polymer film materials are combined with state of the art, scalable 3D-printing, structuring and welding technologies.

STELLAR (Selective Tape-Laying for Cost-Effective Manufacturing of Optimised Multi-Material Components)

- The aim of the Stellar project is to develop the manufacturing process for high-speed placement of carbon, glass and polymer fibre reinforced matrices, to provide the optimum reinforcement, weight and cost profile within a part
- Stellar develops the design methodologies, manufacturing processes, equipment and control systems needed for localised placement of different fibre-reinforced thermoplastic composite tapes

TIALCHARGER (Titanium Aluminide Turbochargers Improved Fuel Economy, Reduced Emissions)

- The TiAlCharger project aims to create a cost-effective, mass producible, low inertia titanium aluminide turbocharger assembly (Weight savings of 60%, reduction on mass moment of inertia of 36%, improving vehicle efficiency by 5% and reducing CO2 emissions by 8%) by Electron Beam Melting (EBM) and Electron Beam Welding (EBW)
- Creates a new IP protectable product and creating/safeguarding ~176 new jobs.

TNO – Netherlands Organisation for Applied Scientific Research

A-FOOTPRINT (Ankle and foot orthotic personalisation via rapid manufacturing)

- The objective of the A-FOOTPRINT project is to develop novel foot and ankle orthoses which are personalised for shape and biomechanical function and can be ready for patient use within 48 hours (enabling improved fit and comfort, functionality, aesthetic appeal and ease of use with better clinical and cost effectiveness)

ADDFACTOR (ADvanced Digital technologies and virtual engineering for mini-Factories)

- ADDFactor proposes the Mini-factories concept - innovative solution for actors involved in the whole supply chain is presented: the relationship between retailers and the manufacturing technologies will be considered and characterised by a new production framework concept.
- Focused on two different levels of manufacturing solutions: At retail environment and at district level when the products are complex and the manufacturing procedures cannot be scaled at local level

BOREALIS (the 3A energy class Flexible Machine for the new Additive and Subtractive Manufacturing on next generation of complex 3D metal parts)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

CASSAMOBILE (Flexible Mini-Factory for local and customised production in a container)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

COMPOLIGHT (Rapid manufacturing of lightweight metal components)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

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CUSTOM-IMD (SME Supply Chain Integration for Enhanced Fully Customisable Medical Implants, using new biomaterials and rapid manufacturing technologies, to enhance the quality of life for EU citizens)

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DIGINOVA (Innovation for Digital Fabrication)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

DIRECTSPARE (Strengthening the industries competitive position by the development of a logistical and technological system for spare parts that is based on on-demand production)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

FLEXRAP (Development of an innovative, modular rapid prototyping system for rigid and flexible models)

- The aim of the FLEXRAP project was to have a high quality rapid prototyping system with more flexibility and functionality than the stereolithography (SLA) type of systems at the price of a concept modelling system or slightly higher.
- Sub-objectives: Development of support material, development of model materials, experimental printer that allows the use of 2 model materials and a support material and development of process and product applications (shoe-industry and development of cheap wax models with a high precision)

HIPR (High-Precision micro-forming of complex 3D parts)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

MANSYS (MANufacturing decision and supply chain management SYStem for Additive Manufacturing)

- ManSYS aims to develop and demonstrate a set of e-supply chain tools to enable the mass adoption of Additive Manufacturing (AM). This will allow businesses to identify and determine the suitability of AM for metal products, and subsequently manage the associated supply-chain issues and facilitating open product evolution.
- Presented solutions: knowledge driven manufacturing process, customisation, automation, self-management and reduced material usage and waste

METAL-PRINT (The development of a new Flexible Manufacturing technique for Highly Detailed, Custom Made Metallic Products by Metal Inkjet Printing)

- A new Flexible Manufacturing (FM) technique for Highly Detailed, Custom Made Metallic Products by Metal Inkjet Printing is developed to increase competitiveness and internationalisation of SMEs in jewellery and electronics manufacturing industry (fulfilling the needs for more complexity in one product at lower cost, increased functions and manufacturing flexibility)
- The industrial development of Metal-print will is demonstrated by case studies, showing a productivity increase by at least 50%, at 50% costs reduction.

NAIMO (NAnoscale Integrated processing of self-organizing Multifunctional Organic Materials)

- NAIMO will develop new multifunctional materials that are processed by solution-based Additive Manufacturing (e.g. direct printing), under quasi-ambient conditions, to form a composite material with designed multi-functionality in an environmentally-friendly way.
- A key outcome of NAIMO will be the set of materials, process and manufacturing capabilities to transform a plastic film substrate into a multifunctional composite (with designed electronic, optical, sensing and magnetic capabilities)

RAMA3DP (Rapid Manufactuting of Products by Improved 3D-printing)

- The overall objective of the project is to develop a3DP technique via new mechanical, material and software methods in order to resolve the mechanical strength, reproducibility, accuracy and colour drawbacks of current RP methods, resulting in acceptable functional end parts and to 'prove' the applicability of the developed 3 DP prototyping/manufacturing technique by developing specific product applications/demonstrators.

Rapid prototyping and tooling industrial applications

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

SASAM (Support Action for Standardisation in Additive Manufacturing)

- By creating and supporting a Standardisation organisation in the field of Additive Manufacturing (AM), SASAM drives the growth of AM to efficient and sustainable industrial processes.

MATERALISE N.V.

A-FOOTPRINT (Ankle and foot orthotic personalisation via rapid manufacturing)

See *TNO – Netherlands Organisation for Applied Scientific Research*

ADDFACTOR (ADvanced Digital technologies and virtual engineering for mini-Factories)

See *TNO – Netherlands Organisation for Applied Scientific Research*

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See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

CUSTOM-IMD (SME Supply Chain Integration for Enhanced Fully Customisable Medical Implants, using new biomaterials and rapid manufacturing technologies, to enhance the quality of life for EU citizens)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

Development of mechanically alloyed powders and laser processing machine for the fabrication of high performance production metal tools

- This project's aim is the realisation of an integrated production system (material/machine/software) for the fabrication of hard metal parts. The main application area of this development is the fabrication of inserts and complete cavities for the mould making sector (plastic injection moulding and nonferrous metal pressure die casting).

DIRECTSPARE (Strengthening the industries competitive position by the development of a logistical and technological system for spare parts that is based on on-demand production)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

FACTORY-IN-A-DAY (Factory-in-a-day)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

INTERAQCT (International Network for the Training of Early stage Researchers on Advanced Quality control by Computed Tomography)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

MANSYS (MANufacturing decision and supply chain management SYStem for Additive Manufacturing)

See *TNO – Netherlands Organisation for Applied Scientific Research*

PHIDIAS (Technology for manufacturing of medical models based on rapid prototyping and medical imaging technique - quality assessment and application development)

- Validation studies in the PHIDIAS project have indicated that medical models are of interest in complex procedures as they cause a reduction in cost and an increase in quality of the surgery.
- Work Areas: Standards will be developed to perform quality control on model, investigate the clinical relevance of medical models, investigate the costs involved and investigate technologies to provide model based medical devices.

RAMATI (Rapid manufacturing of titanium implants)

- The RAMATI project aims at developing Laser Powder Deposition to the production of biomedicai titanium implants for small size, customised prosthesis, for dental, maxilofacial and cranial reconstruction applications, in a one-per-on e basis, in order to allow exact tailoring of the prosthesis to the clinical requirements.
- Benefits are: single-step process, no machining required, highly automated, material purity, manufacturing planning easy possible, turnaround time of a few hours or days and waste-free process

SASAM (Support Action for Standardisation in Additive Manufacturing)

See *TNO – Netherlands Organisation for Applied Scientific Research*

The Welding Institute Ltd (TWI)

AMCOR (Additive Manufacturing for Wear and Corrosion Applications)

- AMCOR will develop and demonstrate Laser Metal Deposition (LMD) industrial manufacturing systems for the deposition of functional graded coatings (FGM) and 3D features onto metallic components
- The solution offers a knowledge driven manufacturing process with significant production benefits; automation, self-management and reduced material usage and waste.

FASTEBM (High Productivity Electron Beam Melting Additive Manufacturing Development for the Part Production Systems Market)

- The development and knowledge created and protected in this project will allow the SME collaborators to exploit the advantage gained through the development of vastly superior Additive Manufacturing (AM) production systems.
- Key outputs: innovative new high power electron beam gun, a Knowledge surrounding the use of the high power electron beam gun and understanding of beam-powder bed interaction

HIRESEBM (High resolution electron beam melting)

- HiResEBM is a partnership between EU SMEs and RTD providers with the aim of developing an electron beam melting (EBM) Additive Manufacturing process to enable the fabrication of high resolution medical implants with optimised porous structures directly from metal powder.
- The objective of HiResEBM is to produce an efficient manufacturing process that will allow any designed porosity to be incorporated into any part of an implant giving complete freedom to design the optimum implant.

HI-STA-PART (High Strength Aluminium Alloy parts by Selective Laser Melting)

- The Hi-StA-Part project aims to demonstrate the viability to produce aerospace grade aluminium parts using Direct Manufacture (DM) - it demonstrates that components and parts can be manufactured with a significant weight reduction, to the required mechanical properties for aerospace applications.

IMPLANT DIRECT

- ImplantDirect will create a cost-effective, faster manufacturing route for orthopaedic, maxillofacial or trauma implants, tailored to the individual needs of patients. The overall project aims are to improve the quality of the implants, reduce the recovery time, improve the quality of life for the patients and reduce the healthcare costs.
- Key innovations: software solution that will allow the surgeon to directly design the implant shape and developing the Selective Laser Melting process

INTRAPID (Innovative inspection techniques for laser powder deposition quality control)

- The project aims to address the problem of the requirement of an inspection process capable of handling the complex evolving forms and provides non-destructive testing techniques with known capabilities.
- Objectives: provide inspection methods for the laser powder deposition and to manufacture a prototype laser powder deposition manufacturing system.

MANSYS (MANufacturing decision and supply chain management SYStem for Additive Manufacturing)

See *TNO – Netherlands Organisation for Applied Scientific Research*

MERLIN (Development of Aero Engine Component Manufacture using Laser Additive Manufacturing)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

OXIGEN (Oxide Dispersion Strengthened Materials for the Additive Manufacture of High Temperature Components in Power Generation)

- OXIGEN develops different (Oxide Dispersion Strengthened (ODS)) alloys individually designed to address specific high temperature materials performance challenges currently limiting power generation component capabilities.
- Will lead to the prospect of higher efficiency power generation turbine systems

TIALCHARGER (Titanium Aluminide Turbochargers Improved Fuel Economy, Reduced Emissions)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

Katholieke Universiteit Leuven

Advanced dental implants manufactured by selective laser sintering

- The overall objective of the project is to develop new dental implants, which have a high biocompatibility at the post-operational stage and over a further long period (for many years) and do not cause any pain to the patient during the operation of implantation.
- Main result: development of bio-inert and corrosion-resistant dental implants with a high bio-compatibility as well as their manufacturing methods by selective laser sintering of Ti powders

Development of mechanically alloyed powders and laser processing machine for the fabrication of high performance production metal tools

See *MATERALISE N.V.*

FACTORY-IN-A-DAY (Factory-in-a-day)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

HI-MICRO (High Precision Micro Production Technologies)

- The Hi-Micro project intends to realise an innovative approach for the design, manufacturing and quality control of tool inserts to achieve significant breakthrough in mass production of precision 3D micro-parts.
- Enables manufacturing technologies, including Additive Manufacturing (AM), micro electrical discharge machining (micro-EDM), micro electro-chemical machining (micro-ECM) and micro-milling

INTERAQCT (International Network for the Training of Early stage Researchers on Advanced Quality control by Computed Tomography)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

PHIDIAS (Technology for manufacturing of medical models based on rapid prototyping and medical imaging technique - quality assessment and application development)

See *MATERALISE N.V.*

Loughborough University

ADM-ERA (Reinforcing Additive Manufacturing research cooperation between the Central Metallurgical Research and Development Institute and the European Research Area)

- The overall aim of the AdM-ERA project is to integrate the Central Metallurgical Research and Development Institute (CMRDI) into the European Research Area (ERA), by developing cooperation with European research and innovation organisations in A) Additive Manufacturing of Ti and CoCr alloys based prostheses, and B) Additive Manufacturing of biocompatible ceramic materials
- Aims to develop the CMRDI research capacities to explore novel applications (e.g., human-specific prostheses from titanium, cobalt chrome and bio-ceramic materials using high energy laser based selective laser melting systems)

ARTIVASC 3D (**Arti**ficial **vas**cularised scaffolds for **3D**-tissue-regeneration)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

CASSAMOBILE (Flexible Mini-Factory for local and customised production in a container)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

CUSTOM-FIT (A knowledge-based manufacturing system, established by integrating Rapid Manufacturing, IST and Material Science to improve the Quality of Life of European Citizens through Custom fit Products)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

DIGINOVA (Innovation for Digital Fabrication)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

SASAM (Support Action for Standardisation in Additive Manufacturing)

See *TNO – Netherlands Organisation for Applied Scientific Research*

AIMME- Asociacion de investigacion de las industrias metalmecanicas, afines y conexas

AEROBEAM (Direct Manufacturing of stator vanes through electron beam melting)

- AEROBEAM is aimed at investigating the mechanical properties of aeronautical Ti6Al4V stator vanes elaborated by EBM. During this project, optimisation of build parameters, characterisation of processed material, characterisation of recycled powder and characterisation of material processed out of recycled powder are performed.

HIRESEBM (High resolution electron beam melting)

See *The Welding Institute Ltd (TWI)*

KARMA (Knowledge Based Process planning and Design for Additive Layer Manufacturing)

- The objective of KARMA is to respond to challenges like properties, dimensional accuracy and surface quality with a knowledge-based engineering system (KBE) that can estimate functional properties of ALM parts automatically and in short time.
- The KBE system will include a database with characterized material and part properties for all major ALM technologies

MANSYS (MANufacturing decision and supply chain management SYStem for Additive Manufacturing)

See *TNO – Netherlands Organisation for Applied Scientific Research*

REPAIR (Future RepAIR and Maintenance for Aerospace industry)

- The Project RepAIR will perform research on future repair and maintenance for the Aerospace industry - repair of aircraft by integrated direct digital manufacturing is the focus
- Through a higher level of automation und fewer stages of production, less personal costs are necessary which therefore reduce the MRO costs.

BCT STEUERUNGS UND DV-SYSTEME GMBH

AMAZE (**Additive Manufacturing A**iming Towards **Z**ero Waste & **E**fficient Production of High-Tech Metal Products)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

AMCOR (Additive Manufacturing for Wear and Corrosion Applications)

See *The Welding Institute Ltd (TWI)*

IMPLANT DIRECT

See *The Welding Institute Ltd (TWI)*

MANSYS (MANufacturing decision and supply chain management SYStem for Additive Manufacturing)

See *TNO – Netherlands Organisation for Applied Scientific Research*

MERLIN (Development of Aero Engine Component Manufacture using Laser Additive Manufacturing)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

LPW TECHNOLOGY LTD

HIRESEBM (High resolution electron beam melting)

See *The Welding Institute Ltd (TWI)*

HI-STA-PART (High Strength Aluminium Alloy parts by Selective Laser Melting)

See *The Welding Institute Ltd (TWI)*

INTRAPID (Innovative inspection techniques for laser powder deposition quality control)

See *The Welding Institute Ltd (TWI)*

MANSYS (MANufacturing decision and supply chain management SYStem for Additive Manufacturing)

See *TNO – Netherlands Organisation for Applied Scientific Research*

MERLIN (Development of Aero Engine Component Manufacture using Laser Additive Manufacturing)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

Philips NV

FACTORY-IN-A-DAY (Factory-in-a-day)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

HIPR (High-Precision micro-forming of complex 3D parts)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

NAIMO (NAnoscale Integrated processing of self-organizing Multifunctional Organic Materials)

See *TNO – Netherlands Organisation for Applied Scientific Research*

NANOMASTER (Graphene based thermoplastic masterbatches for conventional and Additive Manufacturing processes)

- The aims of the NanoMaster project are to reduce the amount of plastic used to make a component by 50% and hence reduce component weight by 50%, at the same time as imparting electrical and thermal functionality. This is achieved by developing the next generation of graphene-reinforced nano-intermediate that can be used in existing high-throughput plastic component production processes.
- focuses on developing processes for large scale rapid production of graphene reinforced plastic intermediate materials which can be integrated into current conventional and Additive Manufacturing processes

PRINCIPLE (Printing concepts for innovative patterning of low-cost electronics with (sub)micron resolution)

- The project investigates the deposition of functional materials for thin-film electronics by so-called additive methods, also referred to as "printable electronics".
- Project stages: investigate new additive methods for (sub-) micrometer deposition, focus on the functional characterisation of materials deposited by printing methods

Siemens AG

BOREALIS (the 3A energy class Flexible Machine for the new Additive and Subtractive Manufacturing on next generation of complex 3D metal parts)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

DIRECTSPARE (Strengthening the industries competitive position by the development of a logistical and technological system for spare parts that is based on on-demand production)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

FACTORY-IN-A-DAY (Factory-in-a-day)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

OXIGEN (Oxide Dispersion Strengthened Materials for the Additive Manufacture of High

See *The Welding Institute Ltd (TWI)*

PHOCAM (Photopolymer based customised Additive Manufacturing technologies)

- This project aims at developing integrated lithography-based Additive Manufacturing systems which will facilitate the processing of photopolymer-based materials for the factory of the future.
- Core-technologies are Digital light processing (DLP) based processes and Two photon polymerisation (2PP)
- Both processes will be tuned to reduce system cost, and significantly increase throughput and reliability at the same time. Goal is to deliver 'first-time-right' strategies for the involved end-users.

SASAM (Support Action for Standardisation in Additive Manufactruring)

See *TNO – Netherlands Organisation for Applied Scientific Research*

Universität Erlangen-Nürnberg

AMAZE (**Additive Manufacturing** **A**iming Towards **Z**ero Waste & **E**fficient Production of High-Tech Metal Products)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

FASTEBM (High Productivity Electron Beam Melting Additive Manufacturing Development for the Part Production Systems Market)

See *The Welding Institute Ltd (TWI)*

PHIDIAS (Technology for manufacturing of medical models based on rapid prototyping and medical imaging technique - quality assessment and application development)

See *MATERALISE N.V.*

SIMCHAIN (Development of physically based simulation chain for microstructure evolution and resulting mechanical properties focused on Additive Manufacturing processes)

See *Fraunhofer – Gesellschaft zur Förderung der angewandten Forschung*

Source: EUPRO database, CORDIS database

7/ Participation of top organisations in the 7th European Framework and H2020 Programmes and their interconnections

Table 34: Participation of Top Organisations in the 7th European Framework and H2020 Programme and their interconnections, coordinators and number of participants (only the 11 most active organisations are listed)

Project AcronymName	AIMME - Asociacion de investigacion de las industrias metalmecanicas, afines y conexas	BCT STEUERUNGS UND DV-SYSTEME GMBH	Fraunhofer-Gesellschaft zur Förderung der angewandten	Katholieke Universiteit Leuven	Loughborough University (LboroU)	LPW TECHNOLOGY LTD	MATERIALISE N_V_	Philips NV	Siemens AG	The Welding Institute Ltd (TWI)	TNO - Netherlands Organisation for Applied Scientific Research	Coordinator or Host Insitution	Total No of Partners	Programm Type	Programme Acronym
Development of mechanically alloyed powders and laser processing machine for the fabrication of high performance production metal tools				1			1					SIRRIS - CRIF (Centre de Recherches Scientifiques et Techniques de l'Industrie des Fabrications Metalliques) / WTCM (Wetenschappelijk En Technisch Centrum Van de Metaalwerkende Nijverheid)	**7**	4th Framework Programme	FP4-BRITE/EURAM 3
Rapid production of enhanced EDM electrodes by powder based Additive Manufacturing			1									Olle Blomquist Verktygs AB	**6**	4th Framework Programme	FP4-BRITE/EURAM 3
Rapid prototyping and tooling industrial applications			3								1	TNO - Netherlands Organisation for Applied Scientific Research	**26**	4th Framework Programme	FP4-BRITE/EURAM 3
RAPIDSHELLS			1									Lost Wax Development Ltd	**5**	5th Framework Programme	FP5-GROWTH
NAIMO								1			1	Universite Libre de Bruxelles (ULB)	**20**	6th Framework Programme	FP6-NMP

Project AcronymName	AIMME - Asociacion de investigacion de las industrias metalmecanicas, afines y conexas	BCT STEUERUNGS UND DV-SYSTEME GMBH	Fraunhofer-Gesellschaft zur Förderung der angewandten	Katholieke Universiteit Leuven	Loughborough University (LboroU)	LPW TECHNOLOGY LTD	MATERIALISE N_V_	Philips NV	Siemens AG	The Welding Institute Ltd (TWI)	TNO - Netherlands Organisation for Applied Scientific Research	Coordinator or Host Insitution	Total No of Partners	Programm Type	Programme Acronym
AMA3DP											1	PTS SOFTWARE BV	**10**	6th Framework Programme	FP6-SME
DM-ERA					1							Central Metallurgical Research and Development Institute	**2**	7th Framework Programme	FP7-INCO
AEROBEAM	1											AIMME - Asociacion de investigacion de las industrias metalmecanicas, afines y conexas	**2**	7th Framework Programme	FP7-JTI
AMAZE		1	1									European Space Agency (ESA)	**28**	7th Framework Programme	FP7-NMP
AMCOR		1								1		The Welding Institute Ltd (TWI)	**15**	7th Framework Programme	FP7-NMP
CASSAMOBILE			1		1		1				1	Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.	**11**	7th Framework Programme	FP7-NMP
FACTORY-IN-A-DAY			1	1			1	1	1			Delft University of Technology	**16**	7th Framework Programme	FP7-NMP
FASTEBM										1		ARCAM AB	**8**	7th Framework Programme	FP7-SME
HI-MICRO				1								Katholieke Universiteit Leuven	**11**	7th Framework Programme	FP7-NMP
HIRESEBM	1					1				1		ARCAM AB	**6**	7th Framework Programme	FP7-SME
HI-STA-PART						1				1		The Welding Institute Ltd (TWI)	**2**	7th Framework Programme	FP7-JTI

Project AcronymName	AIMME - Asociacion de investigacion de las industrias metalmecanicas, afines y conexas	BCT STEUERUNGS UND DV-SYSTEME GMBH	Fraunhofer-Gesellschaft zur Förderung der angewandten	Katholieke Universiteit Leuven	Loughborough University (LboroU)	LPW TECHNOLOGY LTD	MATERIALISE N_V_	Philips NV	Siemens AG	The Welding Institute Ltd (TWI)	TNO - Netherlands Organisation for Applied Scientific Research	Coordinator or Host Insitution	Total No of Partners	Programm Type	Programme Acronym
IC2			1									Raufoss A/S	**16**	7th Framework Programme	FP7-NMP
IMPLANT DIRECT		1								1		The Welding Institute Ltd (TWI)	**9**	7th Framework Programme	FP7-SME
INTERAQCT			1	1			1					Katholieke Universiteit Leuven	**11**	7th Framework Programme	FP7-PEOPLE
MANSYS	1	1				1	1			1	1	The Welding Institute Ltd (TWI)	**12**	7th Framework Programme	FP7-NMP
MERLIN		1	1			1				1		Rolls-Royce plc	**15**	7th Framework Programme	FP7-TRANSPORT
NANOMASTER								1				Netcomposites Ltd	**13**	7th Framework Programme	FP7-NMP
OXIGEN									1	1		The Welding Institute Ltd (TWI)	**11**	7th Framework Programme	FP7-NMP
PHOCAM									1			Technische Universität Wien/ Technical University Vienna (TU Wien)	**7**	7th Framework Programme	FP7-NMP
SASAM					1		1		1		1	TNO - Netherlands Organisation for Applied Scientific Research	**18**	7th Framework Programme	FP7-NMP
SIMCHAIN			1									Universität Bayreuth	**3**	7th Framework Programme	FP7-JTI

Project AcronymName	AIMME - Asociacion de investigacion de las industrias metalmecanicas, afines y conexas	BCT STEUERUNGS UND DV-SYSTEME GMBH	Fraunhofer-Gesellschaft zur Förderung der angewandten	Katholieke Universiteit Leuven	Loughborough University (LboroU)	LPW TECHNOLOGY LTD	MATERIALISE N_V_	Philips NV	Siemens AG	The Welding Institute Ltd (TWI)	TNO - Netherlands Organisation for Applied Scientific Research	Coordinator or Host Insitution	Total No of Partners	Programm Type	Programme Acronym
SMARTLAM			1									Karlsruher Institut für Technologie/Karlsruhe Institute of Technology - KIT	**8**	7th Framework Programme	FP7-NMP
STELLAR			1									Netcomposites Ltd	**9**	7th Framework Programme	FP7-NMP
TIALCHARGER			1							1		The Welding Institute Ltd (TWI)	**9**	7th Framework Programme	FP7-SME
BOREALIS			1						1		1	PRIMA INDUSTRIE SPA	**17**	H2020	FoF-2014
FoFAM											1	Fundacion PRODINTEC	**4**	H2020	FoF-2014
Advanced dental implants manufactured by selective laser sintering				1								Katholieke Universiteit Leuven	**5**	INTAS	INTAS

Source: EUPRO database, CORDIS database, own calculation

8/ List of organisations that actively participated in EU Framework Programmes

Table 35: List of Organisations that actively participated in EU Framework Programmes sorted by country and number of projects

Country	Organisation	Number of project participations
AUS	Monash University (MonashU)	1
AUS	QUEENSLAND UNIVERSITY OF TECHNOLOGY - QLD QUT	1
AUT	AIT Austrian Institute of Technology GmbH	2
AUT	Profactor Produktionsforschungs GmbH	2
AUT	Technische Universität Wien/ Technical University Vienna (TU Wien)	2
AUT	ACP-Information Technology GmbH	1
AUT	BÖHLER EDELSTAHL GMBH	1
AUT	EMIL BROLL GMBH & CO	1
AUT	FH OÖ Studienbetriebs GmbH	1
AUT	IN-VISION DIGITAL IMAGING OPTICS GMBH	1
AUT	Joanneum Research Forschungsgesellschaft mbH	1
AUT	Laserform Hans prihoda	1
AUT	Medizinische Universität Wien/Medical University of Vienna - MUW	1
AUT	Montanuniversität Leoben/University of Mining and Metallurgy Leoben - MU Leoben	1
AUT	NANOTECCENTER WEIZ FORSCHUNGSGESELLSCHAFT MBH	1
AUT	RESEARCH CENTER FOR NON DESTRUCTIVE TESTING GMBH	1
AUT	SUNPLUGGED - SOLARE ENERGIESYSTEME GMBH	1
AUT	Technische Universität Graz (TU Graz)/Graz University of Technology	1
AUT	TIGER COATINGS	1
BEL	MATERIALISE N.V.	13
BEL	Katholieke Universiteit Leuven	6
BEL	LAYERWISE NV	3
BEL	SIRRIS HET COLLECTIEF CENTRUM VAN TECHNOLOGISCHE INDUSTRIE VZW	3
BEL	FLYING-CAM SA	2
BEL	Rsscan International SA	2
BEL	SIRRIS - CRIF (Centre de Recherches Scientifiques et Techniques de l'Industrie des Fabrications Metalliques)/WTCM (Wetenschappelijk En Technisch Centrum Van de Metaalwerkende Nijverheid)	2
BEL	TOYOTA MOTOR ENGINEERING & MANUFACTURING EUROPE SA	2
BEL	DENYS NV	1
BEL	Eeuwfeest Kliniek Antwerpen	1
BEL	EURO HEAT PIPES SA	1
BEL	IMEC (Interuniversity Micro Electronics Center)	1
BEL	IMINDS VZW	1
BEL	KATHOLIEKE HOGESCHOOL KEMPEN (KHK)	1
BEL	MARTEC CONSULTING SPRL	1
BEL	MELOTTE NV	1
BEL	Open Engineering s.a.	1
BEL	Université de Mons	1
BEL	Universite Libre de Bruxelles (ULB)	1
BEL	VCST INDUSTRIAL PRODUCTS BVBA	1
BEL	VELLEMAN SWITCH	1
BEL	VITO - Vlaamse Instelling voor Technologisch Onderzoek NV	1
BGR	Agromachina Sa	1
BGR	ANGEL KANCHEV UNIVERSITY OF ROUSSE	1
BLR	Institute of Technical Acoustic	2
BLR	Belarussian Institute for Postgraduate Medical Education	1
BLR	National Academy of Sciences of Belarus	1
BLR	POWER METALLURGY RESEARCH INSTITUTE	1
CHE	Inspire AG fur Mechatronische Produktionssysteme und Fertigungstechnik	4
CHE	HELIOTIS AG	2
CHE	UNITECHNOLOGIES SA	2
CHE	Alstom	1
CHE	AO-FORSCHUNGSINSTITUT DAVOS	1
CHE	BESTINCLASS SWITZERLAND	1

Country	Organisation	Number of project participations
CHE	DEGRADABLE SOLUTIONS A.G.	1
CHE	DIAM-EDIL SA	1
CHE	Ecole d'ingenieurs de Geneve - Geneva Ingineer School EIG	1
CHE	Ecole Polytechnique Federale de Lausanne - EPFL - Swiss Federal Institute of Technology, Lausanne	1
CHE	Eidgenössische Materialprüfungs- und Forschungsanstalt/Swiss Federal Laboratoires for Materials Testing and Research - EMPA	1
CHE	Fachhochschule Nordwestschweiz FHNW	1
CHE	GLOBAL CLINICAL TRIALS MANAGEMENT AG	1
CHE	ICOTEC AG	1
CHE	LENSWORLD SA	1
CHE	NORBERT SCHLAFLI MASCHINEN	1
CHE	PHONAK AG	1
CHE	SATISLOH PHOTONICS AG	1
CHE	SciProM SArl - Scientific Project Management	1
CHE	Scuola Universitaria Professionale della Svizzera Italiana (SUPSI)	1
CHE	Sulzer Ltd	1
CHE	TIMCAL LTD	1
CHE	ZIMMER GMBH	1
CYP	Cyprus University Of Technology	1
CYP	FREDERICK RESEARCH CENTER	1
CZE	Brno University of Technology / VYSOKE UCENI TECHNICKE V BRNE	2
CZE	Czech Technical University / CESKE VYSOKE UCENI TECHNIKE V PRAZE	1
CZE	SKODA AUTO A.S.	1
DEU	Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.	25
DEU	BCT STEUERUNGS UND DV-SYSTEME GMBH	5
DEU	Siemens AG	5
DEU	Bayerische Julius-Maximilians-Universität Würzburg	4
DEU	EOS GmbH Electro Optical Systems	4
DEU	Friedrich-Alexander-Universität Erlangen-Nürnberg	4
DEU	Karlsruher Institut für Technologie/Karlsruhe Institute of Technology - KIT	4
DEU	Universität Stuttgart/University of Stuttgart	4
DEU	Technische Universität München/Technical University of Munich	3
DEU	3D-MICROMAC AG	2
DEU	BMW Bayerische Motoren Werke AG	2
DEU	DTM GmbH	2
DEU	EADS European Aeronautic Defence and Space Company	2
DEU	Evonik Degussa GmbH	2
DEU	Fockele und Schwarze Stereolithographietechnik Gmbh	2
DEU	Intelligent Laser Applications GmbH	2
DEU	KMS AUTOMATION GMBH	2
DEU	MARCAM ENGINEERING GMBH	2
DEU	Modell Technik Rapid Prototyping GmbH	2
DEU	MTU Aero Engines GmbH	2
DEU	Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen/RWTH Aachen University	2
DEU	SLM GmbH	2
DEU	TLS TECHNIK GMBH & CO. SPEZIALPULVER KG	2
DEU	Universität Bremen/University of Bremen	2
DEU	5AXPERFORMANCE GMBH	1
DEU	AFT AUTOMATION & FEINWERKTECHNIK GMBH	1
DEU	Airbus SAS	1
DEU	Albert-Ludwigs-Universität Freiburg	1
DEU	Albrecht Roeders GmbH & Co. KG	1
DEU	AVANTYS ENGINEERING GMBH & CO. KG	1
DEU	BADEN-WURTTEMBERG: CONNECTED E.V.	1
DEU	BEGO BREMER GOLDSCHLAGEREI WILHELM HERBST GMBH; CO. KG	1
DEU	Beiersdorf AG	1
DEU	Bertrandt AG	1
DEU	BERUFSGENOSSENSCHAFLICHES UNIVERSITAETSKLINIKUM BERGMANNSHEIL GMBH	1
DEU	B-P-E International Dr. Hornig GmbH	1

Country	Organisation	Number of project participations
DEU	CELLASYS GMBH	1
DEU	CENTRUM FUER PROTOTYPENBAU GMBH	1
DEU	CIRP GMBH	1
DEU	CITIM GMBH	1
DEU	COATEMA COATING MACHINERY GMBH	1
DEU	COLANDIS GMBH	1
DEU	CONCEPT - LASER GMBH	1
DEU	CP - CENTRUM FUR PROTOTYPENBAU GMBH	1
DEU	CTG-PRINTTEC GMBH	1
DEU	DAY4 ECOTEC GMBH	1
DEU	Deutsche Lufthansa AG	1
DEU	DEUTSCHES MUSEUM VON MEISTERWERKEN DER NATURWISSENSCHAFT UND TECHNIK	1
DEU	ENSINGER GMBH	1
DEU	Erothitan Titan Implantate	1
DEU	ESI GMBH	1
DEU	Forschungsinstitut für Edelmetalle und Metallchemie e.V.	1
DEU	GABO GESELLSCHAFT für ABLAUFORGANISATION, INFORMATIONSVERARBEITUNG UND KOMMUNIKATIONSORGANISATION GMBH & CO. KG	1
DEU	HAECKER AUTOMATION GMBH	1
DEU	Hahn-Schickard-Gesellschaft für Angewandte Forschung e.V.	1
DEU	HBW-GUBESCH THERMOFORMING GMBH	1
DEU	Helmholtz-Gemeinschaft (HHG)	1
DEU	HUMAN SOLUTIONS GMBH	1
DEU	IHI CHARGING SYSTEMS INTERNATIONAL GMBH	1
DEU	IMPACT-INNOVATIONS-GMBH	1
DEU	INDUTHERM Erwärmungsanlagen GmbH	1
DEU	INNOVATIONLAB GMBH	1
DEU	INTERNATIONAL TECHNOLOGY & PRODUCTS - ITP GMBH	1
DEU	Johannes-Gutenberg-Universität Mainz	1
DEU	JOSCH STRAHLSCHWEISSTECHNIK GMBH	1
DEU	Klöckner Desma Schuhmaschinen GmbH	1
DEU	Laser Bearbeitungs- und Beratungszentrum NRW GmbH	1
DEU	Laser Zentrum Hannover e V	1
DEU	LEIBNIZ-INSTITUT FUR DIE PADAGOGIKDER NATURWISSENSCHAFTEN UND MATHEMATIK AN DER UNIVERSITAT KIEL	1
DEU	LPKF LASER & ELECTRONICS AG	1
DEU	MARTIN HEDGES	1
DEU	Max-Planck-Gesellschaft zur Förderung der Wissenschaften eV (MPG)	1
DEU	Medizinische Dienst der krankenversicherung Schleswig - Holstein	1
DEU	Merck KGaA	1
DEU	MICHAEL HUBERT BARFUSS	1
DEU	MICROTEC GESELLSCHAFT für MIKROTECHNOLOGIE MBH	1
DEU	MSE Micro Systems Engineering GmbH & Co.	1
DEU	N/A	1
DEU	NANOTECMARIN GMBH	1
DEU	Nordcom Medical Systems GmbH	1
DEU	Physikalisch-Technische Bundesanstalt	1
DEU	POLYMEROPTIX GMBH	1
DEU	PRUF-UND FORSCHUNGSINSTITUT PIRMASENS EV	1
DEU	PUTZIER Oberflächentechnik GmbH	1
DEU	Quality Assurance in Radiology and Medicine GmbH	1
DEU	REALIZER GMBH	1
DEU	REISCHAUER GMBH	1
DEU	ROCHLING AUTOMOTIVE AG & CO KG	1
DEU	Ruprecht-Karls-Universität Heidelberg	1
DEU	S.K.M. INFORMATIK GMBH	1
DEU	SCHUNK GMBH & CO KG SPANN- UND GREIFTECHNIK	1
DEU	Senslab - Gesellschaft zur Entwicklung und Herstellung Bioelektrochemischer Sensoren mbH	1
DEU	Stepper Fritz	1

Country	Organisation	Number of project participations
DEU	TECHNISCHE UNIVERSITAET MUENCHEN	1
DEU	Technische Universität Chemnitz-Zwickau	1
DEU	Technische Universität Clausthal/Technical University of Clausthal	1
DEU	Technische Universität Dresden/Dresden University of Technology	1
DEU	Trumpf GmbH	1
DEU	UNICAM SOFTWARE GMBH	1
DEU	Universität - Gesamthochschule Paderborn	1
DEU	Universität Bayreuth	1
DEU	VEREIN ZUR Förderung VON INNOVATION DURCH FORSCHUNG, ENTWICKLUNG UND TECHNOLOGIETRANSFER E.V.	1
DEU	Verfahren und Apparate in der Medizinischen Physik GmbH	1
DEU	VIMECON GMBH	1
DEU	VOLUME GRAPHICS GMBH	1
DEU	Wilhelm Eisenhuth GmbH KG	1
DEU	Wissenschaftsgemeinschaft Gottfried Wilhelm Leibniz e.V.	1
DNK	Danish Technological Institute (DTI)	3
DNK	Technical University of Denmark - Danmarks Tekniske Universitet (DTU)	3
DNK	World Association of Industrial and Technological Research Organisations	3
DNK	ANYBODY TECHNOLOGY A/S	2
DNK	CENTER FOR KULTUR- OG OPLEVELSESOKONOMI OVRIGE VIRKSOMHEDSFORMER	1
DNK	CREATE IT REAL APS	1
DNK	DANISH AEROTECH AS	1
DNK	FJ INDUSTRIES A/S*ODENSE JERNVAREFABRIK FJ STEEL FJ SINTERMETAL	1
DNK	FORCE TECHNOLOGY	1
DNK	IT University of Copenhagen	1
DNK	MICROBOTIC A/S	1
DNK	Novo-Nordisk A/S	1
DNK	POLERTEKNIK APS	1
DNK	RECON A/S	1
DNK	SOPHION BIOSCIENCE A/S	1
DNK	UNIVERSAL ROBOTS AS	1
DNK	University of Southern Denmark - Syddansk Universitet (SDU)	1
EGY	Central Metallurgical Research and Development Institute	1
ESP	AIMME -Asociacion de investigacion de las industrias metalmecanicas, afines y conexas	5
ESP	AIJU Asociacion de Investigacion de la Industria del Juguete, Conexas y Afines	4
ESP	IBV Instituto de Biomecanica de Valencia - Biomechanical Institute of Valencia	4
ESP	AIMPLAS Asociacion de Investigacion de Materiales Plasticos y Conexas	2
ESP	Centro Tecnologico Tekniker	2
ESP	Fundacion Ascamm	2
ESP	Fundacion INASMET Asociacion de Investigacion Metalúrgica del Pais Vasco	2
ESP	ACTIVA DISENO INDUSTRIAL Y GRAFICO SL	1
ESP	AIMEN - Asociacion de Investigacion Metalurgica del Noroeste	1
ESP	ASOCIACION CENTRO DE INVESTIGACION EN TECNOLOGIAS DE UNION LORTEK	1
ESP	ASOCIACION DE EMPRESAS TECNOLOGICAS INNOVALIA	1
ESP	ASOCIACION DE INVESTIGACION PARA LA INDUSTRIA DEL CALZADO Y CONEXAS - INESCOP	1
ESP	ASOCIACION ESPANOLA DE RAPID MANUFACTURING	1
ESP	ATOS SPAIN SA	1
ESP	AUTOMATICA Y CONTROL NUMERICO, S.L.	1
ESP	AVANZARE INNOVACION TECNOLOGICA SL	1
ESP	BARRABES INTERNET S.L.U.	1
ESP	CASA ARTIACH S.A.	1
ESP	CASTMOL TEKNOLAYER S.L.	1
ESP	CEIT - Centro de Estudios e Investigaciones Tecnicas de Guipúzcoa/ Centre for Technical Studies and Investigations of Guipuzcoa)	1
ESP	Construcciones Mecanicas Mares SA	1
ESP	CONSULTORES DE AUTOMATIZACION Y ROBOTICA S.A.	1
ESP	CREACIONES JOVIAR S.L.	1
ESP	Creatividad y Diseno SA	1
ESP	CSIC - Consejo Superior de Investigaciones Cientificas/Higher Council for Scientific Research	1

Country	Organisation	Number of project participations
ESP	DANOBAT S.COOP	1
ESP	EKIN SOCIEDAD COOPERATIVA	1
ESP	ERABERRIKUNTZAN ETA EZAGUTZAN ADITUAK DIREN PERTSONEN MUGIKORTEASUNA SUSTATZEKO ELKARTEA	1
ESP	FÁBRICAS AGRUPADA DE MUÑECAS DE ONIL S.A.	1
ESP	FEDERACIÓN EMPRESARIAL METALÚRGICA VALENCIANA	1
ESP	FUNDACION PRODINTEC	1
ESP	FUNDACION TECNALIA RESEARCH & INNOVATION	1
ESP	GESCABLE SL	1
ESP	Hospital de la Sante Creu i San Pau	1
ESP	IDEKO, Centro Tecnologico de Referencia	1
ESP	INDO LENS GROUP S.L	1
ESP	Industria de Turbo Propulsores SA	1
ESP	Ingenieria Computerizada De Modes SL	1
ESP	Instituto IMDEA - Madrid Institute for Advanced Studies	1
ESP	JUGUETES FEBER INTERNATIONAL, S.A.	1
ESP	JUNQUERA Y DIZ S.L.	1
ESP	LAFITT SA	1
ESP	MICRUX FLUIDIC SL	1
ESP	NANOGAP SUB-NM-POWDER S.A.	1
ESP	NEOS SURGERY S.L	1
ESP	NEW MILLENIUM SPORTS SL	1
ESP	O'GAYAR CONSULTING 2009 SL	1
ESP	PAL ROBOTICS SL	1
ESP	PLASTIASITE S.A	1
ESP	POPULAR DE JUGUETES S.L.	1
ESP	Proyeccion Europlan XXI, SL	1
ESP	SISTEMAS DE CONTROL EN LINEA SA	1
ESP	SPASA	1
ESP	Technitest Ingenieros SL	1
ESP	TWOPTICS SYSTEMS DESIGN SL	1
ESP	UDIAT CENTRE DIAGNOSTIC SA	1
ESP	ULPGC - Universidad de Las Palmas de Gran Canaria/Las Palmas de Gran Canaria University	1
ESP	Universidad de Extremadura - University of Extremadura (UNEX)	1
ESP	Universidad Pública de Navarra - Public University of Navarra	1
ESP	VELYEN ELEVACION Y ENGRASE SL	1
ESP	Xunta Galicia (Regional Government of Galicia)	1
FIN	Aalto University	2
FIN	Oulu Polytechnic, Oulun Seudun Ammattikorkeakoulu, OAMK	2
FIN	VTT Technical Research Centre of Finland	2
FIN	Deskartes Oy	1
FIN	DIARC TECHNOLOGY OY	1
FIN	HELSINGIN YLIOPISTO	1
FIN	JYVASKYLAN YLIOPISTO	1
FRA	EADS European Aeronautic Defence and Space Company	3
FRA	MB PROTO SAS	3
FRA	ALMA CONSULTING GROUP	2
FRA	ARDEJE SARL	2
FRA	Arttic SA	2
FRA	Centre National de la Recherche Scientifique - CNRS	2
FRA	COMMISSARIAT A L'ENERGIE ATOMIQUE (CEA)	2
FRA	ESI GROUP	2
FRA	INDUST RECHERCH PROCEDES APPLICAT LASER ASSOCIATION IREPA LASER	2
FRA	Institut National de Recherche en Informatique et en Automatique (INRIA)	2
FRA	POLE EUROPEEN DE PLASTURGIE	2
FRA	Turbomeca SA	2
FRA	ALTATECH SEMICONDUCTOR SA	1
FRA	ARMINES - Structure de Recherche Contractuelle	1
FRA	ASSOCIATION FRANCAISE DE PROTOTYPAGE RAPIDE	1
FRA	ATECA	1

Country	Organisation	Number of project participations
FRA	BESTINCLASS FRANCE	1
FRA	Centre d'Ingenierie de Recherche et de Transfert de l'ESSTIN - ENGINEERING RESEARCH AND TRANSFER CENTRE OF ESSTIN	1
FRA	Centre de Transfert de Technologie du Mans - ASSOCIATION POUR LES TRANSFERT DE TECHNOLOGIES DU MANS	1
FRA	Centre Technique des Industries Mecaniques (CETIM)	1
FRA	Charlyrobot	1
FRA	ecole Nationale d Ingenieurs de Saint-Etienne	1
FRA	ecole Nationale Superieure de Chimie de MULHOUSE	1
FRA	ecole Nationale Superieure des Mines de Saint-etienne	1
FRA	Ecole normale superieure de Cachan (ENSC)	1
FRA	European Space Agency (ESA)	1
FRA	GEMALTO SA	1
FRA	Institut National Polytechnique de Grenoble (INPG)	1
FRA	LEGRAND S.A.	1
FRA	MAQUETTES ET MODeLES DE LA BRESLE SA	1
FRA	MECACHROME FRANCE SAS	1
FRA	N/A	1
FRA	Parangon SA	1
FRA	PLASTIPOLIS	1
FRA	POLY-SHAPE SAS	1
FRA	PRAGMA INDUSTRIES SAS	1
FRA	Radiall SA	1
FRA	RAYCE SARL	1
FRA	SIEMENS INDUSTRY SOFTWARE SAS	1
FRA	Smith & Nephew Plc	1
FRA	Tecphy S.A.	1
FRA	Thales Group	1
FRA	UNION DE NORMALISATION DE LA MECANIQUE UNM ASSOCIATION	1
FRA	Universite de Lille II (Universite de Droit et Sante)	1
FRA	UNIVERSITÉ DE LORRAINE	1
FRA	Universite DE PICARDIE - JULES VERNE	1
FRA	Universite Paul Sabatier de Toulouse III (UPS)	1
FRA	VIAMECA ASSOCIATION	1
GBR	The Welding Institute Ltd (TWI)	10
GBR	Loughborough University (LboroU)	6
GBR	LPW TECHNOLOGY LTD	5
GBR	University of Cambridge (CU)	4
GBR	University of Manchester (ManU)	4
GBR	Cardiff University (CardiffU)	3
GBR	Cranfield University (CranfieldU)	3
GBR	PEACOCKS MEDICAL GROUP LTD.	3
GBR	University of Liverpool (LivU)	3
GBR	University of Nottingham (NottinghamU)	3
GBR	CENTRE FOR PROCESS INNOVATION LIMITED	2
GBR	DESIGN LED PRODUCTS LTD	2
GBR	Glasgow Caledonian University (GCAL)	2
GBR	Granta Design Ltd	2
GBR	Martello Design Ltd	2
GBR	MATERIALS SOLUTIONS LBG	2
GBR	Netcomposites Ltd	2
GBR	Pera Group	2
GBR	Queen Mary University of London - UOL	2
GBR	Rolls-Royce plc	2
GBR	University of Leeds (LeedsU)	2
GBR	University of Newcastle upon Tyne (NCL)	2
GBR	University of Oxford (OU)	2
GBR	X-Tek Systems Ltd	2
GBR	3D Systems Inc.	1
GBR	3T RPD LIMITED	1
GBR	ADVANCED INSULATION SYSTEMS LTD	1

Country	Organisation	Number of project participations
GBR	APPLIED FUNCTIONAL MATERIALS LIMITED	1
GBR	AQUASIUM TECHNOLOGY LTD	1
GBR	AstraZeneca International	1
GBR	Atlantic Plastics Ltd	1
GBR	Avecia Ltd	1
GBR	BAE Systems PLC	1
GBR	BERGHAUS LIMITED	1
GBR	Bombardier Inc.	1
GBR	Castings Technology International	1
GBR	CGTECH LIMITED	1
GBR	C-Tech Innovation Ltd	1
GBR	De Montfort University - DMU	1
GBR	Delcam Plc	1
GBR	ECONOLYST LIMITED	1
GBR	EMP TOOLING SERVICES LIMITED	1
GBR	ETALON RESEARCH LTD	1
GBR	Finsbury Instruments Ltd	1
GBR	H K RAPID PROTOTYPING LIMITED	1
GBR	Heriot-Watt University (HeriotU)	1
GBR	HUNTSMAN ADVANCED MATERIALS (UK) LIMITED	1
GBR	Institute of Occupational Medicine, UK - IOM	1
GBR	INTELLIGENTSIA CONSULTANTS LTD	1
GBR	INTRINSIQ MATERIALES LIMITED	1
GBR	Iota Sigma	1
GBR	Johnson Matthey plc	1
GBR	JRI ORTHOPAEDICS	1
GBR	Kemsing Engineers Limited	1
GBR	Kingston Computer Consultancy Ltd	1
GBR	KNOWLEDGE INTEGRATION LTD	1
GBR	Lambson Fine Chemicals Ltd	1
GBR	Lost Wax Development Ltd	1
GBR	MCP TOOLING TECHNOLOGIES LTD	1
GBR	Med Design	1
GBR	Medical Models Ltd	1
GBR	MICROSEMI SEMICONDUCTOR LIMITED	1
GBR	National Physical Laboratory (NPL)	1
GBR	OLYMPUS TECHNOLOGIES LIMITED	1
GBR	Photonic Science Ltd	1
GBR	Plasma Group Science	1
GBR	Plastic Logic Ltd	1
GBR	PRA TRADING LTD	1
GBR	PRECISION VARIONIC INTERNATIONAL LIMITED	1
GBR	Prometheus Development Ltd	1
GBR	Queen's University of Belfast (QUB)	1
GBR	Rapra Technology Ltd	1
GBR	Renishaw PLC	1
GBR	Smith & Nephew Plc	1
GBR	SPARK POWER LTD	1
GBR	Styles Precision Components Ltd	1
GBR	Swansea University - SwanU	1
GBR	THE MANUFACTURING TECHNOLOGY CENTRE LIMITED LBG	1
GBR	UK Materials Technology Research Institute	1
GBR	United Kingdom Atomic Energy Authority (UKAEA)	1
GBR	University College London - UCL - UOL	1
GBR	University of Birmingham (BirmU)	1
GBR	University of East Anglia (UEA)	1
GBR	University of Edinburgh (EdinburghU)	1
GBR	University of Exeter - ExU	1
GBR	University of Glasgow (GlasU)	1
GBR	University of Greenwich - GreU	1
GBR	University of Teesside (TeesU)	1

Country	Organisation	Number of project participations
GBR	University of the West of England, Bristol - UweU	1
GBR	University of Warwick (WarwickU)	1
GBR	Walter Frank & Sons Ltd	1
GBR	XAAR TECHNOLOGY LIMITED	1
GBR	Xaarjet Ltd	1
GBR	Xennia Technology Ltd	1
GRC	University of Patras	3
GRC	Anthony Th. Katsanos E.M.E.V. SA	1
GRC	FORTH, Foundation for Research and Technology - Hellas	1
GRC	IDRYMA EVGENIDOU	1
GRC	INTERSPORT ATHLETICS S.A.	1
GRC	METALWORKS OF ATTICA SA	1
GRC	PANEPISTIMIO KRITIS (UNIVERSITY OF CRETE)	1
GRC	PYROGENESIS SA	1
HRV	PET-EKO D.O.O.	1
HUN	77 ELECTRONICS MÛSZERIPARI KFT. (77 ELECTRONICS PRECISION ENGINEERING Ltd)	1
HUN	Budapesti Mueszaki es Gazdasagtudomanyi Egyetem - Budapest University of Technology and Economics (BME)	1
IRL	ADAMA INNOVATIONS LTD	1
IRL	CROSPON LIMITED	1
IRL	Dublin City University - DCU	1
IRL	FIREFLY ORTHOSES LIMITED	1
IRL	NATIONAL UNIVERSITY OF IRELAND, GALWAY	1
ISL	Ensk Forsida Icetec -Technological Institute of Iceland (ITI)	1
ISL	Ossur Hf	1
ISR	OBJET GEOMETRIES LTD	1
ISR	WEIZMANN INSTITUTE OF SCIENCE	1
ITA	Consiglio Nazionale delle Ricerche - CNR	4
ITA	FIAT Gruppo	3
ITA	MATRES SCRL	3
ITA	MBN Nanomaterialia SPA	3
ITA	Politecnico di Torino	2
ITA	Universita degli Studi di Palermo/University of Palermo	2
ITA	ALMA MATER STUDIORUM-UNIVERSITA DI BOLOGNA	1
ITA	APR SRL	1
ITA	Avio SPA	1
ITA	AVIOPROP SRL	1
ITA	Bytest SRL	1
ITA	Centro Laser SCRL	1
ITA	Centro Tessile Cotoniero e Abbigliamento SPA	1
ITA	Consorzio Interuniversitario Nazionale per la Scienza e Tecnologia dei Materiali (INSTM)	1
ITA	D'Appolonia SPA	1
ITA	Democenter - Centro di Servizi per la Diffusione dell Automazione Industriale SCRL	1
ITA	Ducati Motor Holding SPA	1
ITA	ENGINEERING - INGEGNERIA INFORMATICA SPA	1
ITA	Erreci Rapid Casting SRL	1
ITA	EUROCOATING S.P.A.	1
ITA	GMP Poliuretani SRL	1
ITA	GREY MER SRL	1
ITA	Innova SPA	1
ITA	Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro (INAIL)	1
ITA	Istituto per le Ricerche di Tecnologia Meccanica e per l Automazione (RTM) SPA	1
ITA	LATI INDUSTRIA TERMOPLASTI SPA	1
ITA	MANUDIRECT S.R.L.	1
ITA	Mavet SRL	1
ITA	MI-ME MINUTERIE METALLICHE MELES SPA	1
ITA	Nava SRL	1
ITA	OFFICINA ORTOPEDICA MICHELOTTI SRL	1
ITA	Politecnico di Milano	1

Country	Organisation	Number of project participations
ITA	Prima Industrie SpA	1
ITA	Sem Srl	1
ITA	Sider ARC SRL	1
ITA	Software 80 Srl	1
ITA	STMicroelectronics NV	1
ITA	SYNESIS CONSORZIO CON ATTIVITA ESTERNA	1
ITA	TESSITURA CARLO MAJOCCHI & C SPA	1
ITA	TWOCARE SRL	1
ITA	Universita degli Studi di Padova/University of Padova	1
ITA	Universita degli Studi di Perugia/University of Perugia	1
ITA	Universita degli Studi di Salerno/University of Salerno	1
ITA	Universita degli Studi di Torino/University of Turin	1
ITA	VAMP TECHNOLOGIES S.P.A.	1
ITA	VIBRAM SPA	1
ITA	WISILDENT SRL	1
LIE	LISTEMANN AG WERKSTOFF UND WAERMEBEHANDLUNGSTECHNIK	1
LTU	BALTIC ORTHOSERVICE UAB	1
LUX	INTELLIGENTSIA CONSULTANTS SÀRL	1
NLD	TNO - Netherlands Organisation for Applied Scientific Research	16
NLD	Philips NV	5
NLD	Universiteit Maastricht	4
NLD	Berenschot BV	3
NLD	BPO NEDERLAND BV	2
NLD	PROMOLDING BV	2
NLD	University Medical Center Utrecht	2
NLD	XPAND BIOTECHNOLOGY BV	2
NLD	Adema & Touw BV	1
NLD	ADVANCED FIBRE PLACEMENT TECHNOLOGY BV	1
NLD	AIRBORNE TECHNOLOGY CENTER B.V.	1
NLD	ATELIER LE MARQUIS V.O.F.	1
NLD	BOSCH REXROTH	1
NLD	BOYD INTERNATIONAL B.V.	1
NLD	CELLCOTEC BV	1
NLD	CLINICAL TRIAL CENTER MAASTRICHT	1
NLD	Delft University of Technology	1
NLD	DSM BV	1
NLD	Eindhoven University of Technology	1
NLD	Erasmus Universiteit Rotterdam/Erasmus University Rotterdam	1
NLD	FACTORY CONTROL BV	1
NLD	Fontys Hogeschool Eindhoven	1
NLD	FORMATEC TECHNICAL CERAMICS BV	1
NLD	HYDRAUVISION BV	1
NLD	INNALOX BV	1
NLD	JANSEN CHARLOTTE ISABELLE - CHARLOTTE JANSEN INDUSTRIEEL ONTWERP PRINTED JEWELRY	1
NLD	KEY MANAGEMENT CONSULT B.V.	1
NLD	KMWE PRECISIE EINDHOVEN BV	1
NLD	LACQUEY BV	1
NLD	Mareco Gereedschapmakerij BV	1
NLD	Metaalgieterij Kinheim BV	1
NLD	MORENO / ATELIER DE BRUIJN	1
NLD	NEBATO MODULE & APPARATENBOUW B.V.	1
NLD	Nederlands Normalisatie-Instituut	1
NLD	NTS MECHATRONICS.V.	1
NLD	OCE Technologies BV	1
NLD	OLED TECHNOLOGIES BV	1
NLD	PTS SOFTWARE BV	1
NLD	Radboud Universiteit Nijmegen	1
NLD	RANDSTAD NEDERLAND BV	1
NLD	RIJKSUNIVERSITEIT GRONINGEN	1

Country	Organisation	Number of project participations
NLD	STEGGE BEHEER BV	1
NLD	STICHTING PROTOSPACE	1
NLD	SUPRAPOLIX BV	1
NLD	Universiteit Twente	1
NLD	Universiteit Utrecht/Utrecht University	1
NLD	WEI CONSULTING	1
NOR	Raufoss A/S	4
NOR	SINTEF - Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology/NTNU	2
NOR	BALDUR COATINGS AS	1
NOR	KERANOR AS	1
NOR	NORSK TITANIUM COMPONENTS AS	1
NOR	Norwegian University of Science and Technology - Norges Teknisk-Naturvitenskapelige Universitet (NTNU)	1
NOR	PLASTO AS	1
NOR	VERKSTEDPARTNER AS	1
NOR	VISITECH AS	1
POL	Technical University of Lodz / Politechnika Lodzka	2
POL	Wroclaw University of Technology / Politechnika Wroclawska	2
POL	ENTE SPOLKA. Z OGRANICZONA.ODPOWIEDZIALNOSCIA.	1
POL	Metal Forming Institute / Instytut Obrobki Plastycznej	1
POL	POLKOM BADANIA SP ZOO	1
POL	UNIWERSYTET JAGIELLONSKI	1
POL	Wytwornia Sprzetu Komunikacyjnego 'PZL-Rzeszow' Spolka Akcyjna	1
PRT	UTL - Universidade Tecnica de Lisboa, Technical University of Lisbon	2
PRT	CENTITVC - CENTRO DE NANOTECNOLOGIAE MATERIAIS TECNICOS FUNCIONAIS EINTELIGENTES ASSOCIACAO	1
PRT	CRITICAL MANUFACTURING SA	1
PRT	INEGI - Instituto de Engenharia Mecanica e Gestao Industrial/Institute of Mechanical Engineering and Industrial Management	1
PRT	INESC - Instituto de Engenharia de Sistemas e Computadores/Institute for Systems and Computer Engineering	1
PRT	INETI - Instituto Nacional de Engenharia, Tecnologia e Inovacao/National Institute for Industrial Engineering and Technology	1
PRT	INSTITUTO DE EDUCAÇÃO DA UNIVERSIDADE DE LISBOA	1
PRT	IPL Instituto Politecnico de Leiria	1
PRT	OPTICA PITA LDA	1
PRT	PORTCAST - Fundicao Nodular SA	1
PRT	TJ Moldes Lda	1
PRT	UL Universidade de Lisboa - University Of Lisbon	1
PRT	Universidade de Aveiro - University of Aveiro (UA)	1
ROU	COGEME SET RO SRL	1
ROU	MICROELECTRONICA S.A.	1
ROU	SITEX 45 SRL	1
ROU	Technical University of Cluj-Napoca / UNIVERSITATEA TEHNICA DIN CLUJ-NAPOCA	1
ROU	UNIVERSITATEA VALAHIA TARGOVISTE	1
ROU	UNIVERSITY OF MEDICINE AND PHARMACY VICTOR BABES TIMISOARA	1
RUS	Russian Academy of Sciences	3
RUS	Institute of Metallurgy	2
RUS	INSTITUTE OF SOLID STATE CHEMISTRY AND MECHANOCHEMISTRY	1
RUS	Institute of System Investigations	1
RUS	Physical Metallurgy Institute	1
RUS	State Technological University	1
SVK	3R TECHNICS SLOVAKIA SRO	1
SVN	REGIONAL TECHNOLOGICAL CENTRE ZASAVJE (REGIONALNI TEHNOLOSKI CENTER ZASAVJE)	2
SVN	ALCOM PROIZVODNJA IN TRGOVINA DOO	1
SVN	FOTONA PROIZVODNJA OPTOELEKTRONSKIH NAPRAV D.D.	1
SVN	INTERESANSA - INSTITUT ZA RAZVOJ IN IZDELOVALNE TEHNOLOGIJE - ZAVOD	1
SVN	UCS, KUPCU PRILAGOJENI PROIZVOIDI DOO	1
SWE	ACREO SWEDISH ICT AB	3

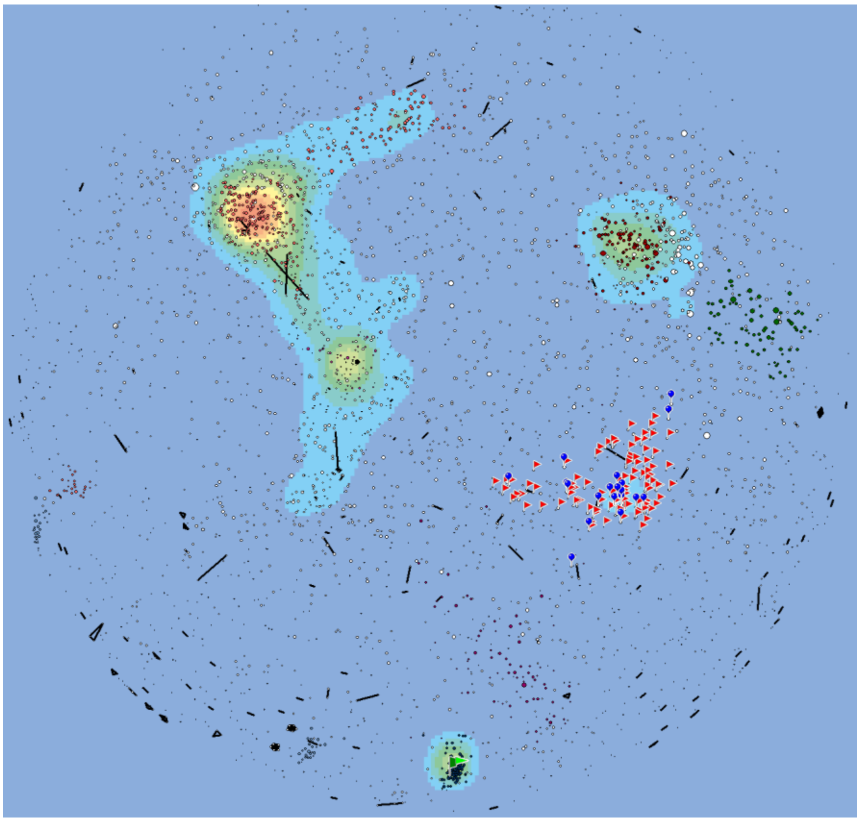
Country	Organisation	Number of project participations
SWE	ARCAM AB	3
SWE	Royal Institute of Technology - Kungliga Tekniska Högskolan (KTH)	3
SWE	Olle Blomquist Verktygs AB	2
SWE	Swerea IVF	2
SWE	Acron Formservice AB	1
SWE	ELOS MEDTECH MICROPLAST AB	1
SWE	FCUBIC AB	1
SWE	GKN AEROSPACE SWEDEN AB	1
SWE	Högskolan Väst	1
SWE	Linköping University (LIU)	1
SWE	Mitthögskolan (Mid Sweden University)	1
SWE	N/A	1
SWE	OMNISYS INSTRUMENTS AB	1
SWE	ORTOMA AB	1
SWE	SIS, SWEDISH STANDARDS INSTITUTE	1
SWE	TRUSTOR PRECISION COMPONENTS AB	1
SWE	Volvo Group	1
SWE	XAAR JET AB	1
TUR	ARTIDOKSAN HIZLI IMALAT TEKNOLOJILERI SANAYI VE TICARET AS	3
TUR	BOGAZICI UNIVERSITESI	1
TUR	GE MARMARA TECHNOLOGY CENTER MUHENDISLIK HIZMETLERI LIMITED SIRKETI	1
TUR	HEKSAGON MUHENDISLIK VE TASARIM AS	1
UKR	Iwtschenko Progress	1
USA	THE BOEING COMPANY CORPORATION	1

Source: EUPRO database, CORDIS database, own calculation

9/ Example of analysis of research front: micro-stereolithography

Location in the Science Map

Figure 150: Bibliographically Coupled Publications, local density of similar publications; parameters: 200/10



Source: Web of Science, own calculation

Table 36: Disciplines of the Research Front "Micro-Stereolithography"

Discipline	No. of publications in this Research Front	No. of Publications in total
Nanoscience & Nanotechnology	29	273
Engineering, Mechanical	25	646
Chemistry, Multidisciplinary	22	155
Materials Science, Multidisciplinary	20	1469
Engineering, Manufacturing	18	793
Physics, Applied	14	443
Biochemical Research Methods	11	50
Engineering, Electrical & Electronic	10	291
Instruments & Instrumentation	9	83
Materials Science, Ceramics	7	95
Chemistry, Analytical	5	47
Chemistry, Physical	5	136
Optics	5	303
Automation & Control Systems	5	197
Engineering, Biomedical	4	406
Physics, Condensed Matter	4	85
Biophysics	3	47
Engineering, Industrial	3	165
Physics, Fluids & Plasmas	3	20
Crystallography	2	6

Source: Web of Science, own calculation

Table 37: List of keywords for the Research Front "Micro-Stereolithography"

Keyword	No. of publications in this Research Front	No. of Publications in total
Microstereolithography	9	13
MASK IMAGE PROJECTION	4	5
Photopolymerisation	6	29
DMD	4	6
Alumina	5	20
Stereolithography	14	202
MASK IMAGE PLANNING	3	3
Projection-microstereolithography	2	2
Reactionware	2	2
Scanning-projection	2	2
DEFORMATION CONTROL	2	2
3D-printed microfluidic	2	2
Dynamic mask	2	2
Scanning projection stereolithography	2	2
Pixel Blending	2	2
PROJECTION-BASED STEREOLITHOGRAPHY PROCESS	2	2
Photopolymerizable ceramic suspensions	2	2
Projection lithography	2	2
Exposure	2	2
Minutes	2	2
Microstereolithography (mu SL)	2	2
Mask Projection Stereolithography Process	2	2
Mask pattern	2	2
BULK LITHOGRAPHY	2	2
High-speed fabrication	2	2
Large area exposure	2	2
Ceramic microstereolithography	2	2

Source: IDEA Consult, AIT and VTT, 2015

Pioneering Publications

Sensors and Actuators A: Physical

Volume 121, Issue 1, 31 May 2005, Pages 113–120

Projection micro-stereolithography using digital micro-mirror dynamic mask

C. Sun, N. Fang, D.M. Wu, X. Zhang

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doi:10.1016/j.sna.2004.12.011

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Abstract

We present in this paper the development of a high-resolution projection micro-stereolithography (PμSL) process by using the Digital Micromirror Device (DMD™, Texas Instruments) as a dynamic mask. This unique technology provides a parallel fabrication of complex three-dimensional (3D) microstructures used for micro electro-mechanical systems (MEMS). Based on the understanding of underlying mechanisms, a process model has been developed with all critical parameters obtained from the experimental measurement. By coupling the experimental measurement and the process model, the photon-induced curing behavior of the resin has been quantitatively studied. The role of UV doping has been thereafter justified, as it can effectively reduce the curing depth without compromising the chemical property of the resin. The fabrication of complex 3D microstructures, such as matrix, and micro-spring array, with the smallest feature of 0.6 μm, has been demonstrated.

Keywords

Three-dimensional microfabrication; Projection micro-stereolithography; Dynamic mask; Polymer

Source: http://www.sciencedirect.com/science/article/pii/S0924424704008672

Sensors and Actuators A: Physical

Volume 77, Issue 2, 12 October 1999, Pages 149–156

Micro-stereolithography of polymeric and ceramic microstructures

X Zhang, X.N Jiang, C Sun

Show more

doi:10.1016/S0924-4247(99)00189-2

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Abstract

Micro-stereolithography (μSL) is a novel micro-manufacturing process which builds the truly 3D microstructures by solidifying the liquid monomer in a layer by layer fashion. In this work, an advanced μSL apparatus is designed and developed which includes an Ar^+ laser, the beam delivery system, computer-controlled precision x–y–z stages and CAD design tool, and in situ process monitoring systems. The 1.2 μm resolution of μSL fabrication has been achieved with this apparatus. The microtubes with high aspect ratio of 16 and real 3D microchannels and microcones are fabricated on silicon substrate. For the first time, μSL of ceramic microgears has been successfully demonstrated.

Keywords

Stereolithography; MEMS; Micromachining; Microfabrication; Polymer; Ceramics

Source: http://www.sciencedirect.com/science/article/pii/S0924424799001892

Cure depth control for complex 3D microstructure fabrication in dynamic mask projection microstereolithography

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Ryan B. Wicker (W.M. Keck Center for 3D Innovation, The University of Texas at El Paso, El Paso, Texas, USA)
Seok-Hyun Cho (School of Mechanical Engineering, Pusan National University, Busan, South Korea)
Chang-Sik Ha (Department of Polymer Science and Engineering, Pusan National University, Busan, South Korea)
Seok-Hee Lee (School of Mechanical Engineering, Pusan National University, Busan, South Korea)

Citation: Jae-Won Choi, Ryan B. Wicker, Seok-Hyun Cho, Chang-Sik Ha, Seok-Hee Lee, (2009) "Cure depth control for complex 3D microstructure fabrication in dynamic mask projection microstereolithography", Rapid Prototyping Journal, Vol. 15 Iss: 1, pp.59 - 70

DOI http://dx.doi.org/10.1108/13552540910925072

Acknowledgements: This work was supported by Grant No. R01-2004-000-10507-0 from the Basic Program of the Korea Science & Engineering Foundation, the Mr and Mrs. MacIntosh Murchison Chair I in Engineering endowment at the University of Texas at El Paso (UTEP), and a research contract from the US Army Space and Missile Defense Command and the Homeland Protection Institute to the Center for Defense Systems Research at UTEP. The findings and opinions presented in this paper are those of the authors and do not necessarily reflect those of the sponsors of this research.

Abstract:

Purpose

– The paper's aim is to explore a method using light absorption for improving manufacturing of complex, three-dimensional (3D) micro-parts with a previously developed dynamic mask projection microstereolithography (MSL) system. A common issue with stereolithography systems and especially important in MSL is uncontrolled penetration of the ultraviolet light source into the photocrosslinkable resin when fabricating down-facing surfaces. To accurately fabricate complex 3D parts with down-facing surfaces, a chemical light absorber, Tinuvin 327™ was mixed in different concentrations into an acrylate-based photocurable resin, and the solutions were tested for cure depths and successful micro-part fabrication.

Source: http://www.emeraldinsight.com/doi/abs/10.1108/13552540910925072

Table 38: Recent Publications within the Research Front " Micro-Stereolithography"

Authors	Title	Year
He, Yong; Wu, Wen-bin; Fu, Jian-zhong	Rapid fabrication of paper-based microfluidic analytical devices with desktop stereolithography 3D-printer	2015
Comina, German; Suska, Anke; Filippini, Daniel	3D-printed Unibody Lab-on-a-Chip: Features Survey and Check-Valves Integration dagger	2015
Lee, Michael P.; Cooper, Geoffrey J. T.; Hinkley, Trevor; Gibson, Graham M.; Padgett, Miles J.; Cronin, Leroy	Development of a 3D-printer using scanning projection stereolithography	2015
Hwang, Yongha; Paydar, Omeed H.; Candler, Robert N.	3D-printed molds for non-planar PDMS microfluidic channels	2015
Chen, Cong; Li, Minglei; Gao, Yanjing; Nie, Jun; Sun, Fang	A study of nanogels with different polysiloxane chain lengths for photopolymerisation stress reduction and modification of polymer network properties	2015
Xu, Kai; Chen, Yong	Mask Image Planning for Deformation Control in Projection-Based Stereolithography Process	2015
Rogers, Chad I.; Qaderi, Kamran; Woolley, Adam T.; Nordin, Gregory P.	3D-printed microfluidic devices with integrated valves	2015
Emami, Mohammad Mandi; Barazandeh, Farshad; Yaghmaie, Farrokh	An analytical model for scanning-projection based stereolithography	2015
Adake, Chandrashekhar V.; Bhargava, Parag; Gandhi, Prasanna	Effect of surfactant on dispersion of alumina in photopolymerizable monomers and their UV curing behavior for microstereolithography	2015
Gentry, Susan P.; Halloran, John W.	Light scattering in absorbing ceramic suspensions: Effect on the width and depth of photopolymerized features	2015
Comina, German; Suska, Anke; Filippini, Daniel	Low cost lab-on-a-chip prototyping with a consumer grade 3D-printer	2014
Chen, Teng-Hao; Lee, Semin; Flood, Amar H.; Miljanic, Ognjen S.	How to print a crystal structure model in 3D	2014
Kitson, Philip J.; Macdonell, Andrew; Tsuda, Soichiro; Zang, HongYing; Long, De-Liang; Cronin, Leroy	Bringing Crystal Structures to Reality by Three-Dimensional Printing	2014
Hoai Viet Nguyen; Tmejova, Katerina; Krejcova, Ludmila; Hynek, David; Kopel, Pavel; Kynicky, Jindrich; Adam, Vojtech; Kizek, Rene	Electrochemical Characterisation of PNA Oligonucleotide of Neuraminidase Gene	2014
Erkal, Jayda L.; Selimovic, Asmira; Gross, Bethany C.; Lockwood, Sarah Y.; Walton, Eric L.; McNamara, Stephen; Martin, R. Scott; Spence, Dana M.	3D-printed microfluidic devices with integrated versatile and reusable electrodes	2014
Shallan, Aliaa I.; Smejkal, Petr; Corban, Monika; Guijt, Rosanne M.; Breadmore, Michael C.	Cost-Effective Three-Dimensional Printing of Visibly Transparent Microchips within Minutes	2014
Wang, Xiaolong; Guo, Qiuquan; Cai, Xiaobing; Zhou, Shaolin; Kobe, Brad; Yang, Jun	Initiator-Integrated 3D-printing Enables the Formation of Complex Metallic Architectures	2014
Goswami, Ankur; Ankit, K.; Balashanmugam, N.; Umarji, Arun M.; Madras, Giridhar	Optimisation of rheological properties of photopolymerizable alumina suspensions for ceramic microstereolithography	2014
Chisholm, Greig; Kitson, Philip J.; Kirkaldy, Niall D.; Bloor, Leanne G.; Cronin, Leroy	3D-printed flow plates for the electrolysis of water: an economic and adaptable approach to device manufacture	2014
Zhong, Kejun; Gao, Yiqing; Li, Feng; Luo, Ningning; Zhang, Weiwei	Fabrication of continuous relief micro-optic elements using real-time maskless lithography technique based on DMD	2014

Source: Web of Science

Table 39: Key Scientists within the Research Front "Micro-Stereolithography"

Authors	Publications	Citations	Affiliation
Cronin, Leroy	9	143	[Symes, Mark D.; Kitson, Philip J.; Yan, Jun; Richmond, Craig J.; Cooper, Geoffrey J. T.; Cronin, Leroy] Univ Glasgow, WestCHEM, Sch Chem, Glasgow G12 8QQ, Lanark, Scotland; [Bowman, Richard W.] Univ Glasgow, Sch Phys & Astron, Glasgow G12 8QQ, Lanark, Scotland; [Vilbrandt, Turlif] Uformia AS, N-9062 Furuflaten, Norway
Chen, Yong	8	12	[Zhou, Chi; Chen, Yong; Waltz, Richard A.] Univ So Calif, Daniel J Epstein Dept Ind & Syst Engn, Los Angeles, CA 90089 USA
Kitson, Philip J.	8	143	[Symes, Mark D.; Kitson, Philip J.; Yan, Jun; Richmond, Craig J.; Cooper, Geoffrey J. T.; Cronin, Leroy] Univ Glasgow, WestCHEM, Sch Chem, Glasgow G12 8QQ, Lanark, Scotland; [Bowman, Richard W.] Univ Glasgow, Sch Phys & Astron, Glasgow G12 8QQ, Lanark, Scotland; [Vilbrandt, Turlif] Uformia AS, N-9062 Furuflaten, Norway
Zhou, Chi	6	12	[Zhou, Chi; Chen, Yong; Waltz, Richard A.] Univ So Calif, Daniel J Epstein Dept Ind & Syst Engn, Los Angeles, CA 90089 USA
Filippini, Daniel	4	20	[Preechaburana, Pakorn; Filippini, Daniel] Linkoping Univ, Div Appl Phys, IFM, Opt Devices Lab, S-58183 Linkoping, Sweden; [Preechaburana, Pakorn] Thammasat Univ, Fac Sci & Technol, Dept Phys, Pathum Thani 12120, Thailand
Choi, Jae-Won	4	36	[Choi, Jae-Won; MacDonald, Eric; Wicker, Ryan] Univ Texas El Paso, WM Keck Ctr, El Paso, TX 79968 USA; [Choi, Jae-Won; Wicker, Ryan] Univ Texas El Paso, Dept Mech Engn, El Paso, TX 79968 USA; [MacDonald, Eric] Univ Texas El Paso, Dept Elect & Comp Engn, El Paso, TX 79968 USA
Rosen, David W.	4	9	[Jariwala, Amit S.; Ding, Fel; Zhao, Xiayun; Rosen, David W.] Georgia Inst Technol, George W Woodruff Sch Mech Engn, Atlanta, GA 30332 USA
Gandhi, Prasanna	4	0	[Gandhi, Prasanna] Indian Inst Technol, Dept Mech Engn, Suman Mashruwala Adv Microengn Lab, Bombay 400076, Maharashtra, India
Jariwala, Amit S.	4	9	[Jariwala, Amit S.; Ding, Fel; Zhao, Xiayun; Rosen, David W.] Georgia Inst Technol, George W Woodruff Sch Mech Engn, Atlanta, GA 30332 USA
Kang, Hyun-Wook	3	41	[Jung, Jin Woo; Kang, Hyun-Wook; Kang, Tae-Yun; Park, Jeong Hun; Park, Jaesung; Cho, Dong-Woo] Pohang Univ Sci & Technol, Dept Mech Engn, Pohang 790784, Gyeongbuk, South Korea; [Cho, Dong-Woo] Pohang Univ Sci & Technol, Div Integrat Biosci & Biotechnol, Pohang 790784, Gyeongbuk, South Korea
Bhole, Kiran	3	0	[Gandhi, Prasanna] Indian Inst Technol, Dept Mech Engn, Suman Mashruwala Adv Microengn Lab, Bombay 400076, Maharashtra, India
Cho, Dong-Woo	3	46	[Sohn, You Sun; Jung, Jin Woo; Cho, Dong-Woo] Pohang Univ Sci & Technol, Dept Mech Engn, Pohang 790784, Gyungbuk, South Korea; [Kim, Jong Young] Andong Natl Univ, Dept Mech Engn, Andong 760749, Gyungbuk, South Korea; [Cho, Dong-Woo] Pohang Univ Sci & Technol, Div Integrat Biosci & Biotechnol, Pohang 790784, Gyungbuk, South Korea
Comina, German	3	12	[Comina, German; Suska, Anke; Filippini, Daniel] Linkoping Univ, IFM, Dept Phys Chem & Biol, Opt Devices Lab, S-58183 Linkoping, Sweden
Goswami, Ankur	3	7	[Madras, Giridhar] Indian Inst Sci, Dept Chem Engn, Bangalore 560012, Karnataka, India; [Goswami, Ankur; Umarji, A. M.] Indian Inst Sci, Mat Res Ctr, Bangalore 560012, Karnataka, India
Madras, Giridhar	3	7	[Madras, Giridhar] Indian Inst Sci, Dept Chem Engn, Bangalore 560012, Karnataka, India; [Goswami, Ankur; Umarji, A. M.] Indian Inst Sci, Mat Res Ctr, Bangalore 560012, Karnataka, India
Sans, Victor	3	63	[Kitson, Philip J.; Rosnes, Mali H.; Sans, Victor; Dragone, Vincenza; Cronin, Leroy] Univ Glasgow, Sch Chem, Glasgow G12 8QQ, Lanark, Scotland
Suska, Anke	3	12	[Comina, German; Suska, Anke; Filippini, Daniel] Linkoping Univ, IFM, Dept Phys Chem & Biol, Opt Devices Lab, S-58183 Linkoping, Sweden
Rosnes, Mali H.	3	63	[Kitson, Philip J.; Rosnes, Mali H.; Sans, Victor; Dragone, Vincenza; Cronin, Leroy] Univ Glasgow, Sch Chem, Glasgow G12 8QQ, Lanark, Scotland
Kim, Ho-Chan	3	28	[Ha, Young-Myoung; Park, In-Baek; Lee, Seok-Hee] Pusan Natl Univ, Sch Mech Engn, Pusan 609735, South Korea; [Kim, Ho-Chan] Andong Natl Univ, Sch Mech Engn, Andong 760749, South Korea
Halloran, John W.	3	5	[Bae, Chang-Jun; Halloran, John W.] Univ Michigan, Ann Arbor, MI 48109 USA

Source: Web of Science, own calculation

Table 40: Research Organisations (not standardized) within the Research Front "Micro-Stereolithography"

Organisation	No. of publications in this Research Front	No. of Publications in total	No of Citations In research Front
Univ So Calif, Daniel J Epstein Dept Ind & Syst Engn, Los Angeles, CA 90089 USA	6	11	12
Univ Glasgow, Sch Chem, Glasgow G12 8QQ, Lanark, Scotland	5	10	64
Indian Inst Sci, Mat Res Ctr, Bangalore 560012, Karnataka, India	3	21	7
Indian Inst Technol, Dept Mech Engn, Suman Mashruwala Adv Microengn Lab, Bombay 400076, Maharashtra, India	3	5	0
Univ Texas El Paso, Dept Mech Engn, El Paso, TX 79968 USA	3	26	35
Georgia Inst Technol, Sch Chem & Biomol Engn, Atlanta, GA 30332 USA	2	8	11
Univ Glasgow, WestCHEM, Sch Chem, Glasgow G12 8QQ, Lanark, Scotland	2	18	65
Univ So Calif, Epstein Dept Ind & Syst Engn, Los Angeles, CA 90089 USA	2	19	0
Univ Nottingham, Fac Engn, Mfg Res Div, Nottingham NG7 2RD, England	2	7	0
Korea Adv Inst Sci & Technol, Dept Chem & Biomol Engn, Taejon 305701, South Korea	2	7	54
Univ Michigan, Dept Mat Sci & Engn, Ann Arbor, MI 48109 USA	2	13	3
Georgia Inst Technol, George W Woodruff Sch Mech Engn, Atlanta, GA 30332 USA	2	8	8
Univ Illinois, Dept Mech Sci & Engn, Urbana, IL 61801 USA	2	5	19
Univ Illinois, Dept Mat Sci & Engn, Urbana, IL 61801 USA	2	15	59
Indian Inst Sci, Dept Chem Engn, Bangalore 560012, Karnataka, India	2	21	6
Univ Glasgow, Sch Chem, WestCHEM, Glasgow G12 8QQ, Lanark, Scotland	2	16	14
St Louis Univ, Dept Chem, St Louis, MO 63103 USA	2	12	21
Amirkabir Univ Technol, NTRC, Tehran 1591633311, Iran	2	7	2
MIT, Dept Mech Engn, Cambridge, MA 02139 USA	2	3	9
Xi An Jiao Tong Univ, State Key Lab Mfg Syst Engn, Xian 710049, Peoples R China	2	19	8

Source: Web of Science, own calculation

10/ Case study selection: overview of primary information sources

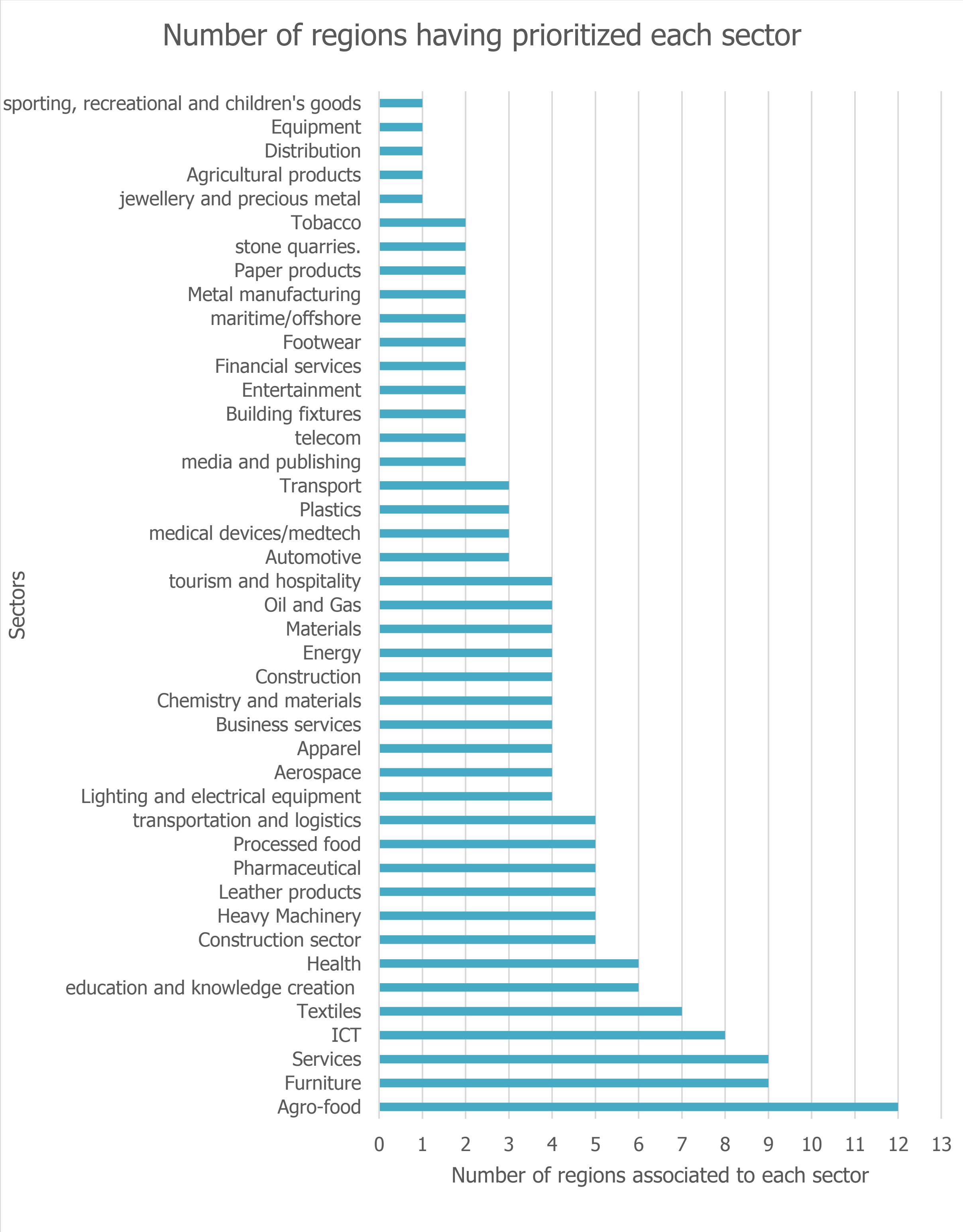
Name	Link
Primary Sources	
The Smart Specialisation Platform or the "Eye@S³ Tool" of the IPTS	*Link:* *http://s3platform.jrc.ec.europa.eu/home* *and* *http://s3platform.jrc.ec.europa.eu/map*
Regional Innovation Monitor Plus	*Link:* *https://ec.europa.eu/growth/tools-databases/regional-innovation-monitor/*
Reports and indicators from the Cluster Observatory	*Link:* *http://www.clusterobservatory.eu*
Secondary Sources	
ERAWATCH	*Link:* *http://erawatch.jrc.ec.europa.eu/erawatch/opencms/information/reports/reg_level/?country=-1*
EUROSTAT data	*Link:* *http://ec.europa.eu/eurostat/statistics-explained/index.php/Structural_business_statistics_at_regional_level*
Web-based sources (used in a very occasional fashion):	• Official websites from the **regional governments** under the scope • **EU Service Innovation Scoreboard** o Link: http://ec.europa.eu/growth/tools-databases/esic/scoreboard/esis-database/index_en.htm • **OECD** reports on Regional Innovation Policy and the OECD Innovation Policy Platform • **National** Statistics Offices • **Intermediary** sources (EU or sub-EU platforms as well as federations and similar intermediates)

Source: IDEA Consult, 2015

11/ Regional prioritization – Sectoral Overview

The regions were associated to specific sectors. The aggregated results are presented below in the sectoral overview below.

Figure 151: Sectoral Overview



Source: IDEA Consult, 2015

In order to provide a more detailed view on the sectoral affiliation of each region, the following list illustrates the connections between each sector and each of the regions that remained under the scope of the selection process.

1. **Agro-food**: Groningen, Helsinki-Uusimaa region, Lithuania (instead of only Aukštaitija and Samogitia for which no public information seems to be available), Lubelskie, Malopolskie, Midi-Pyrénées, North-Vest, Region of Thessalia, Severoiztochen, Southern and Eastern Ireland, Southern Denmark Region, Yugoiztochen
2. **Processed food**: Burgenland, Kujawsko-Pomorskie, Lower Austria, Podlaskie, Voivodship, Region of Thessalia
3. **Tobacco**: Groningen, Region of Thessalia
4. **Agricultural products**: Region of Thessalia
5. **Textiles**: "Croatia proper", Lubelskie, Malopolskie, Marche, North east, North-Vest, Yugoiztochen,
6. **Leather products**: Centre, "Croatia proper", Lisbon, Rhône-Alpes, Severoiztochen
7. **Apparel**: Centre, "Croatia proper", Kujawsko-Pomorskie, Yugoiztochen
8. **Footwear**: Centre, Stredni Morava
9. **Sporting, recreational and children's goods**: Stredni Morava
10. **Tourism and hospitality**: Border, Midland and Western, Helsinki-Uusimaa region, North east, Severoiztochen
11. **Services**: Utrecht, Dolnoslaskie, Helsinki-Uusimaa region, Ile-de-France, Lancashire / North West England, Lithuania (instead of only Aukštaitija and Samogitia for which no public information seems to be available), Marche, Midi-Pyrénées, Southern and Eastern Ireland
12. **ICT**: Utrecht, Border, Midland and Western, Dolnoslaskie, Helsinki-Uusimaa region, North east, North-Vest, Prague/Praha, Severoiztochen
13. **Business services**: Utrecht, Corse, Lancashire / North West England, Lisbon
14. **Media and publishing**: Lisbon, Prague/Praha
15. **Telecom**: Lithuania (instead of only Aukštaitija and Samogitia for which no public information seems to be available), Prague/Praha
16. **Entertainment**: Corse, Ile-de-France
17. **Financial services**: Utrecht, Corse
18. **Health**: Utrecht, Helsinki-Uusimaa region, Midi-Pyrénées, North east, Northern Ireland, Southern Denmark Region
19. **Pharmaceutical**: Border, Midland and Western, Central Hungary, Midi-Pyrénées, Prague/Praha, Rhône-Alpes
20. **Medical devices/medtech**: Border, Midland and Western, Rhône-Alpes, Southern and Eastern Ireland
21. **Construction sector**: Bratislava Region, Corse, Southern and Eastern Ireland
22. **Construction**: Dolnoslaskie, Lancashire / North West England, Region of Thessalia, Southern Denmark Region
23. **Building fixtures**: Burgenland, Lubelskie
24. **Stone quarries**: Border, Midland and Western, Malopolskie
25. **Heavy Machinery**: Central Hungary, Marche, Podkarpackie, Podlaskie Voivodship, Yugoiztochen
26. **Transport**: Dolnoslaskie, North-Vest, Southern and Eastern Ireland
27. **Transportation and logistics**: Central Hungary, Ile-de-France, Lisbon, Lithuania (instead of only Aukštaitija and Samogitia for which no public information seems to be available), Southern Denmark Region
28. **Aerospace**: Ile-de-France, Lancashire / North West England, Midi-Pyrénées, Podkarpackie
29. **Automotive**: Dolnoslaskie, Lancashire / North West England, Podkarpackie
30. **Maritime/offshore**: Podlaskie Voivodship, Yugoiztochen
31. **Oil and Gas**: Central Hungary, Centre, Groningen, Lower Austria
32. **Energy**: Lithuania (instead of only Aukštaitija and Samogitia for which no public information seems to be available), Lubelskie, Southern Denmark Region, Stredni, Morava
33. **Chemistry and materials**: Bratislava Region, Malopolskie, Rhône-Alpes, Severoiztochen
34. **Materials**: Bratislava Region, Malopolskie, Northern Ireland, Stredni Morava
35. **Plastics**: Bratislava Region, Kujawsko-Pomorskie, Podkarpackie
36. **Metal manufacturing**: Lower Austria, Marche
37. **Paper products**: Kujawsko-Pomorskie, Marche
38. **Jewellery and precious metal**: Groningen
39. **Distribution**: Lisbon
40. **Equipment**: Lower Austria

12/ Regional selection workshop: Agenda

The Internal Workshop was organized in two sessions and followed the agenda presented below.

Morning session – Prioritisation and selection of the key applications

1. Introduction by the team leader
    a. Attendance, project status, debrief from previous client telco and objectives of the session
2. Presentation of the SAM by consortium partners
    a. Process followed
    b. Results
    c. Issues and challenges
3. Tour de table – first comments from the participants on the SAM
4. Rows and columns at stake: comments on specific items
    a. Structure of the grid
    b. The sectoral divide
    c. The applications
    d. Content
    e. Structure of the grid
    f. The sectoral divide
    g. The applications
    h. Content
5. Listing of the points of attention and Validation of the final SAM
6. Wrap-up of the session by the team leader

Afternoon Session – Allocation of the regions to the 16 selected applications

1. Introduction by the team leader
    a. Attendance and objectives of the session
2. Presentation of the regional grid by the team leader
    b. Process followed
    c. Results
    d. Issues and challenges
3. Tour de table – Comments on the grid and relevant adjustments/complements
4. Discussion on the regions to be selected – ROUND 1
    e. Open Question: are there regions that are missing in the grid and should be added to the list?
    f. Open question: is there information in the grid that is missing or incorrect?
    g. Scoping question: what are the main clusters we should prioritise (aerospace? Etc.)?
5. Discussion on the regions to be selected – ROUND 2

h. Selection question: which are the less relevant regions we could leave aside?

i. What are the regions corresponding to each of the main clusters (10 clusters in total)

j. Validation of the 25 candidate regions (+ 5 optional regions) for each of the 10 clusters (to become case studies)

6. Conclusion of the workshop and presentation of the uptake of its results and next steps

13/ Indicative list of key players

Name of the player	Country (headquarter)	Type of organisation	Listed in the context of…
3A	France	SME	Metallic structural parts for airplane
3d Gence	Poland	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups, etc.), sculptures, and others
3d Hubs	Netherlands	Large Company	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
3d Mania	Slowakia	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
3D Microprint GmbH (Laser sintering)	Germany	SME	3D-printed textiles
3D Prima	Sweden	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
3d Solutions	Austria	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
3D Systems (including Layerwise, HK 3D and Phenix, recently absorbed)	United States of America	Large Company	Metal AM for injection Molding, Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others, Plastic-based car interior components, Inert and hard implants, Surgical planning
3D Systems / Cubify	United States of America	Large Company	3D-printed textiles
3dChef	Netherlands	SME	3D-printed confectionery
3DScannersUK	United Kingdom	SME	Plastic-based car interior components
915 labs	United States of America	SME	3D-printed confectionery
Aachen University	Germany	RTO	Metallic structural parts for airplane, Plastic-based car interior components, Metal AM for injection Molding
Aalto University	Finland	RTO	Inert and hard implants, Surgical planning
ABB	Switzerland	Large company	Affordable Houses
Adidas	Germany	Large Company	3D-printed textiles
Advanced Powders & Coatings (AP&C)	Canada	Large Company	Metal AM for injection Molding
Afinia	United States of America	SME	3D-printed textiles
AI Design	United States of America	Large Company	Plastic-based car interior components
Air Liquide	France	Large company	Affordable Houses
Airbus (incl. AvioSpace)	France	Large Company	Metallic structural parts for airplane
Aittip technology centre	Spain	RTO	Inert and hard implants Surgical planning

Albyco.be	Belgium	SME	Plastic-based car interior components
Alfa Laval	Sweden	Large Company	Spare parts for machines
Alphacam	DE	Large Company	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Altair	Germany	Large Company	Metallic structural parts for airplane Metal AM for injection Molding
AMPS	Australia	Large Company	Metallic structural parts for airplane
Anatomics	Australia	SME	Inert and hard implants Surgical planning
Aoku3d Limited	Hong Kong, China	SME	3D-printed textiles
APNC – Canada Powder	Canada	SME	Metallic structural parts for airplane
Arburg	Germany	Large Company	3D-printed textiles
Arcam	Sweden	Large Company	Plastic-based car interior components
Arcam AB	Sweden	Large Company	Spare parts for machines, Inert and hard implants, Surgical planning, Metallic structural parts for airplane
Arcelor Mittal	India	Large company	Affordable Houses
Arkema	France	Large Company	Plastic-based car interior components Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
ARUP Group	United Kingdom	Large company	Affordable Houses
ASERM (Asociacion Espanola de Rapid Manufacturing)	Spain	Intermediary	Plastic-based car interior components
ASML	Netherlands	Large Company	Spare parts for machines
ATI	United States of America	Large Company	Metal AM for injection Molding, Metallic structural parts for airplane
AtlasCopCO	Sweden	Large Company	Spare parts for machines
Aubert et Duval (ERAMET)	France	Large Company	Metallic structural parts for airplane
Audi	Germany	Large Company	Plastic-based car interior components
Autodesk (including FIT and Netfob, recently absorbed)	United States of America	Large Company	Affordable Houses, Metallic structural parts for airplane, Plastic-based car interior components, Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
BAE Systems	United Kingdom	Large Company	3D-printed textiles
Barilla	Italy	Large company	3D-printed confectionery
BASF	Germany	Large company	Affordable Houses
Bayar	Germany	Large Company	Inert and hard implants, Surgical planning
Berenschot	Netherlands	Large Company	Spare parts for machines
Berker	Germany	Large Company	Metal AM for injection Molding
BetAbram	Slovenia	SME	Affordable Houses

Bibus Austria GmbH	Austria	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Bim IT	Germany	RTO	Plastic-based car interior components
BiomedZimmer	Switzerland	Large Company	Surgical planning, Inert and hard implants
Biozoon Food Innovations GmbH	Germany	SME	3D-printed confectionery
BKL Lasertechnik	Germany	SME	Metal AM for injection Molding
Blok Group	Netherlands	Large Company	Spare parts for machines
BMW	Germany	Large Company	Plastic-based car interior components, Spare parts for machines
Boeing	United States of America	Large Company	Metallic structural parts for airplane
Bombardier	Canada	Large Company	Metallic structural parts for airplane
Bosch	Germany	Large Company	Metal AM for injection Molding
Brno University	Czech Republic	RTO	Metal AM for injection Molding
Brugges Raytech	Belgium	SME	Metal AM for injection Molding
Brunel University	United Kingdom	RTO	3D-printed textiles
Buchan Concrete Solutions	United Kingdom	Large company	Affordable Houses
Bugatti	Italy	Large Company	Plastic-based car interior components
Bureau Happold	United Kingdom	Large company	Affordable Houses
CA Models	Scotland	SME	Metal AM for injection Molding
Cambridge Design Partnership	United Kingdom	SME	Plastic-based car interior components
Cardiff University	United Kingdom	RTO	3D-printed textiles
Carglass	France	Large Company	Spare parts for machines
Carpenter	United States of America	Large Company	Metal AM for injection Molding, Metallic structural parts for airplane
cc-products	Germany	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others, 3D-printed textiles
CEIT Biomedical Engineering	*Slovakia*	*SME*	Inert and hard implants, Surgical planning
Center for Smart Manufacturing (CSM) am FH OÖ Campus Wels	Austria	RTO	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Centexbel	Belgium	RTO	3D-printed textiles
CETIM	France	RTO	Metallic structural parts for airplane, Metal AM for injection Molding, Inert and hard implants, Surgical planning
Cirp	Germany	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Classictacho	Germany	SME	Plastic-based car interior components
Cobot	Germany	SME	3D-printed textiles

CocaCola	United States of America	Large company	3D-printed confectionery
COESIA Group	Italy	Large Company	Spare parts for machines
Colorfabb	The Netherlands	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others, 3D-printed textiles
COMAC	China	Large Company	Metallic structural parts for airplane
ConceptLaser	Germany	SME	Metallic structural parts for airplane Metal AM for injection Molding Spare parts for machines Plastic-based car interior components Inert and hard implants? Surgical planning
Constellium	Netherlands	Large Company	Metallic structural parts for airplane
Continuum Fashion	United States of America	SME	3D-printed textiles
Cornell University	United States of America	RTO	3D-printed confectionery Affordable Houses
CRAFT - Center for Rapid Automated Fabrication Technologies (University of Southern California)	United States of America	RTO	Affordable Houses
Cranfield University	United Kingdom	RTO	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others, Metallic structural parts for airplane
CRC 814 (collaborative research center for AM within the University of Erlangen-Nuremberg (FAU)	Germany	RTO	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
CRDM (now 3D Systems)	UK target bought by USA	Large company	Affordable Houses
Creative-tools	Sweden	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
CTIF	France	RTO	Metallic structural parts for airplane
CVMR Corporation	United States of America	Large Company	Metal AM for injection Molding
Daimler	Germany	Large Company	Plastic-based car interior components
Danish Technological Institute	Denmark	RTO	3D-printed confectionery
DAS FILAMENT	Germany, EU	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Dash CAE	United Kingdom	SME	Plastic-based car interior components
Dassault Systèmes	France	Large Company	Metallic structural parts for airplane Plastic-based car interior components Metal AM for injection Molding Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
DDD Printservice	Germany, Austria	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls,

			cups etc.), sculptures, and others
De Grood Innovations	Netherlands	SME	3D-printed confectionery
DePuy Synthes Spine (part of Johnson and Johnson)	Verenigde Staten	Large Company	3D-printed spinal implants
Direct Manufacturing Research Center (University of Padeborn)	Germany	RTO	Metallic structural parts for airplane, Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
D-M-E MoldFusion	United States	Large Company	Metal AM for injection Molding
DMG Mori	Japan	Large Company	Spare parts for machines Metal AM for injection Molding
DMU	United Kingdom	RTO	Inert and hard implants
Dos Cielos	Spain	SME	3D-printed confectionery
Dovetailed Ltd	United Kingdom	SME	3D-printed confectionery
DPH International	France	SME	Metal AM for injection Molding
Dream3D	United Kingdom	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Drexel University	United Kingdom	RTO	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
DSM	Netherlands	Large company	3D-printed textiles
DSM (SOMOS)	Netherlands	Large Company	Plastic-based car interior components
Dublin College University; Dublin City University	Ireland	RTO	3D-printed textiles
Dus Architects	Netherlands	SME	Affordable Houses
Dutch Filaments	Netherlands	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Eberspaecher	Germany	Large Company	Plastic-based car interior components
ECKA Granuls	Germany	Large Company	Metallic structural parts for airplane
Ecole des Mines	France	RTO	Metal AM for injection Molding
Edag	Germany	Large Company	Plastic-based car interior components
Electroloom	United States of America	SME	3D-printed textiles
Emerging Objects	United States of America	SME	Affordable Houses
eMotion Tech	France	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Envisiontec	United States of America	Large Company	Metal AM for injection Molding Inert and hard implants Surgical planning
EOS	Germany	SME	Metallic structural parts for airplane Plastic-based car interior components Metal AM for injection Molding Spare parts for machines Lighting and other home decoration products, such as

			furniture, vessels (vases, bowls, cups etc.), sculptures, and others Affordable Houses Inert and hard implants Surgical planning 3D-printed textiles
EPSRC Centre for Innovative Manufacturing in Additive Manufacturing	United Kingdom	RTO	Affordable Houses
Equi-Sphere	Canada	Large Company	Metallic structural parts for airplane
Equus Automotive	United States of America	Large Company	Plastic-based car interior components
Erasteel	Germany	Large Company	Metal AM for injection Molding
Eriks	Netherlands	Large Company	Spare parts for machines
ERNE Holzbau	Switzerland	SME	Affordable Houses
ETH Zürich	Switzerland	RTO	Affordable Houses
Eurasteel EU	Belgium	Large Company	Metallic structural parts for airplane
Eurocopter	France	Large Company	Spare parts for machines
Eurotungstene (ERAMET)	France	Large Company	Metal AM for injection Molding
Evonik	Germany	Large Company	Metallic structural parts for airplane and Spare parts for machines Plastic-based car interior components Spare parts for machines Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
EVO-tech GmbH	Austria	SME	3D-printed textiles
Exnovo	Italy	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
ExOne	United States	Large Company	Metallic structural parts for airplane Plastic-based car interior components Metal AM for injection Molding Inert and hard implants Surgical planning
Extrudr (FD3D GmbH)	Austria	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Fab Lab Foundation	Worldwide	Large Company	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Fabberhouse by Alphacam GmbH	Germany		Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Fabberworld	Switzerland	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Fabbulos GmbH	Austria	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls,

			cups etc.), sculptures, and others
Faberdashery	United Kingdom	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Fachhochschule Nordwestschweiz	Switzerland	RTO	Inert and hard implants Surgical planning
Faurecia	France	Large Company	Plastic-based car interior components
Faurecia	France	Large Company	Metal AM for injection Molding
Fazer Group	Finland	Large company	3D-printed confectionery
Feetz	United States of America	SME	3D-printed textiles
FELIXprinters	Netherlands	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Ferrari	Italy	Large Company	Plastic-based car interior components
Fiat	Italy	Large Company	Plastic-based car interior components
Filamentum	Netherlands	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
FIMATEC	Finland	SME	Affordable Houses
Finmecannica	Italy	Large Company	Metallic structural parts for airplane
Fit Production	Germany	SME	Inert and hard implants Surgical planning
Fives	France	Large Company	Spare parts for machines
FKM Laser Sintering	Germany	SME	Plastic-based car interior components
footprintfootwear	United States of America	SME	3D-printed textiles
Ford	United States of America	Large Company	Plastic-based car interior components
Formlabs	United States of America	Started out of MIT in 2011	3D-printed textiles
Foster and Partners	United Kingdom	SME	Affordable Houses
Fraunhofer (incl. institutes such as ILT, IWS, IZM, etc.)	Germany	RTO	Metallic structural parts for airplane Metal AM for injection Molding Spare parts for machines Spare parts for machines Inert and hard implants Surgical planning Plastic-based car interior components Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others; 3D-printed textiles
Freedom of Creation by 3D Systems (US)	United States	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
FUSIA	France	SME	Metallic structural parts for airplane
Gässling	Sweden	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others

GE Healthcare	United Kingdom	Large company	Inert and hard implants Surgical planning
General Electrics	United States of America	Large Company	Spare parts for machines, Plastic-based car interior components
General Electrics (incl. AvioAero)	United States of America	Large Company	Metallic structural parts for airplane
German RepRap GmbH	Germany	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Ghent University	Belgium	RTO	3D-printed textiles
GKN	United Kingdom	Large Company	Metallic structural parts for airplane Metal AM for injection Molding
Google	United States of America	Large Company	Metallic structural parts for airplane
Google (SketchUp)	United States	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Goose	United Kingdom	SME	3D-printed textiles
Gorgé (including Polyshape and Initial, recently absorbed)	France	Large Company	Metal AM for injection Molding
GP Tromans Associates	United Kingdom	SME	Plastic-based car interior components
Grainger & Worrall	United Kingdom	Large Company	Metal AM for injection Molding
H.C. Starck	Germany	Large Company	Metallic structural parts for airplane
HARATECH Manfred Haiberger e.U.	Austria	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Heijmans	Netherlands	Large company	Affordable Houses
Helm X	United Kingdom	Large company	Affordable Houses
Henkel	Germany	Large company	Affordable Houses
Hershey's Inc.	United States of America	Large company	3D-printed confectionery
Hewlett Packard	United States of America	Large Company	Plastic-based car interior components
High Value Manufacturing Catapult	United Kingdom	Intermediary	Plastic-based car interior components
Höganäs	Sweden	Large Company	Injection molding
Honda	Japan	Large Company	Plastic-based car interior components
Honeywell	United States of America	Large Company	Metallic structural parts for airplane
Hyundai Engineering and Construction	Korea	Large company	Affordable Houses
IAC - International Automotive Components	Luxembourg	Large Company	Plastic-based car interior components
IGo3D	Germany	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
IHI Corporation	Japan	Large Company	Metallic structural parts for airplane
IKEA	Netherlands	Large Company	Metal AM for injection Molding
Imaginarium	India	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls,

			cups etc.), sculptures, and others
Infineon Technologies AG	Germany	Large Company	3D-printed textiles
Innofil3D BV	Netherlands	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
INSA	France	RTO	Metallic structural parts for airplane
Inspire AG	Switzerland	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Institute for Advanced Architecture of Catalonia (IAAC)	Spain	RTO	Affordable Houses
Institute for Computational Design (Faculty of Architecture and Urban Planning, University of Stuttgart)	Germany	RTO	Affordable Houses
Institute for Rapid Product Development (IRPD)	Switzerland	RTO	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Iris van Herpen	Denmark / France	SME	3D-printed textiles
IRTES LERMPS	France	RTO	Metal AM for injection Molding
Istituto Italiano di Tecnologia Center for Space Human Robotics	Italy	RTO	3D-printed textiles
ITCF Institut für Textilchemie und Chemiefaser Denkendorf	Germany	RTO	3D-printed textiles
Jaguar	United Kingdom	Large Company	Plastic-based car interior components
Janne Kyttanen	Finland	SME	3D-printed textiles
Jenny Sabin Studio	United States of America	SME	Affordable Houses
Jiri Evenhuis	Netherlands	SME	3D-printed textiles
Johnson and Johnson	United States	Large company	Inert and hard implants Surgical planning
Johnson Controls Inc	United States of America	Large Company	Plastic-based car interior components
Katjes Fassin Ltd.	United Kingdom and Germany	SME	3D-printed confectionery
KDI Polymer Specialists Ltd.	United Kingdom	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
KIA	Korea	Large Company	Plastic-based car interior components
Koenigsegg	Sweden	Large Company	Plastic-based car interior components Spare parts for machines
KOR Ecologic	Canada	SME	Plastic-based car interior components
Krones AG	Germany	Large Company	Spare parts for machines
KUKA	Germany	Large company	Affordable Houses
KUL, department of Mechanical engineering	Belgium	RTO	Surgical planning Inert and hard implants
Kushner Studios	United States of America	SME	Affordable Houses
L'Oréal	France	Large Company	Metal AM for injection Molding

La Boscana	Spain	SME	3D-printed confectionery
Lafarge Tarmac	United Kingdom	Large company	Affordable Houses
Lamborghini	Italy	Large Company	Plastic-based car interior components
Landré	Netherlands	SME	Spare parts for machines
Laser Prototypes Europe	Northern ireland	Large Company	Metal AM for injection Molding
Laser Zentrum Hannover	Germany	RTO	Plastic-based car interior components
Laser Zentrum Nord	Germany	RTO	Metallic structural parts for airplane
LayerLab.net.GmbH	Austria	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Layerwise (Part of 3Dsystems)	Belgium	Large Company	Spare parts for machines Inert and hard implants Surgical planning
Leapfrog 3D-printers	The Netherlands	SME	3D-printed textiles
Lego	Denmark	Large Company	Metal AM for injection Molding
Lehrmann & Voss & Co.	Germany	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Lima Corporate	Italy	SME	Inert and hard implants Surgical planning
Local Motors	United States of America	SME	Plastic-based car interior components
Loughborough University	United Kingdom	RTO	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Loughborough University (Innovative Manufacturing and Construction Research Centre)	United Kingdom	RTO	Affordable Houses
Loughborough University, Additive Manufacturing Research Group	United Kingdom	RTO	Surgical planning Inert and hard implants
LPW	United Kingdom	Large Company	Metallic structural parts for airplane Metal AM for injection Molding Plastic-based car interior components
LSN Diffusion	United Kingdom	Large Company	Metal AM for injection Molding
Maastricht University	The Netherlands	RTO	Inert and hard implants Surgical planning
MakerBot (Stratasys)	United States	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others3D-printed textiles
Mapal	Germany	Large Company	Spare parts for machines
Marfo Food Group	Netherlands	SME	3D-printed confectionery
Maserati	Italy	Large Company	Plastic-based car interior components
Massachusetts Institute of Technology (MIT) Fluid Interfaces Group Media Lab	United States of America	RTO	3D-printed confectionery
Materialise	Belgium	Large Company	Inert and hard implants Metallic structural parts for airplane

			Plastic-based car interior components Metal AM for injection Molding Spare parts for machines Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others Surgical planning3D-printed textiles
Matsuura	Japan	Large Company	Plastic-based car interior components
Mazak	Japan	Large Company	Spare parts for machines
McNeel	United States	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Mecachrome	France	Large Company	Metallic structural parts for airplane
Medacta	Switzerland	SME	Inert and hard implants Surgical planning
Mediated Matter (MIT)	United States of America	RTO	Affordable Houses
Medicrea	France	Large Company	Inert and hard implants Surgical planning
Melotte	Belgium	SME	Metal AM for injection Molding Spare parts for machines Surgical planning
MELT icepops	Netherlands	SME	3D-printed confectionery
Mercedes	Germany	Large Company	Plastic-based car interior components Spare parts for machines
MeshLab	United States	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Messago	Germany	SME	Plastic-based car interior components
Metallo-Chimique N.V.	Belgium	Large Company	Metallic structural parts for airplane
Metalysis	United Kingdom	Large Company	Metal AM for injection Molding
MGX - Materialise headquarters	Belgium	Large company	3D-printed textiles
Milan Cluster on Additive Manufacturing	Italy	Intermediary	Plastic-based car interior components
Mines de Paris	France	RTO	Metallic structural parts for airplane
MK Technology GmbH	Germany	SME	Metal AM for injection Molding
Mobelife (part of Materialise)	Belgium	SME	Inert and hard implants Surgical planning
Modern Meadow	United States of America	SME	3D-printed confectionery
Moldex3D	United States of America	Large Company	Metal AM for injection Molding
Monolite UK Ltd.	United Kingdom	SME	Affordable Houses
MTU Aero Engines	Germany	Large Company	Metallic structural parts for airplane
Multec GmbH	Germany	SME	3D-printed textiles
MX3D	Netherlands	SME	Affordable Houses
Nanosteel	United States of America	Large Company	Metal AM for injection Molding
Nanovia	France	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
NASA	United States of America	Public entity	3D-printed confectionery

NCCR Digital Fabrication (National Centre of Competence in Research)	Switzerland	RTO	Affordable Houses
Neofil3D	France	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Nervous System	United States of America	SME	3D-printed textiles
Nestle	Switzerland	Large company	Metal AM for injection Molding 3D-printed confectionery Spare parts for machines
Netfabb	Germany	Large Company	Metallic structural parts for airplane, Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Network for sustainable building and administering in cold climates	Sweden	RTO /network	Affordable Houses
New Balance	United Kingdom	Large Company	3D-printed textiles
NewCastle University School of Mechanical and Systems Engineerding	United Kingdom	RTO	Inert and hard implants Surgical planning
Niederrhein University of Applied Sciences	Germany	RTO	3D-printed textiles
Nike	United States of America	Large Company	3D-printed textiles
Ninjaflex – part of Fenner Drives, Inc.	United States of America	Large company	3D-printed textiles
Noa Raviv	United States of America	SME	3D-printed textiles
Northrop Grumman	United States of America	Large Company	Metallic structural parts for airplane
Nottingham University, Additive Manufacturing and 3D-printing Reseach Group, Nothingham university	United Kingdom	RTO	Inert and hard implants, Surgical planning
NPI National Physical Laboratory	United Kingdom	RTO	3D-printed textiles
Ogle Models Prototypes	United Kingdom	SME	Plastic-based car interior components
Omega Plastics	United Kingdom	Large Company	Metal AM for injection Molding
Onshape by Pinshape	United States	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Open Edge	France	SME	3D-printed textiles
Optomec	United States	Large company	Inert and hard implants Surgical planning
Orbi-Tech GmbH	Germany	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Patria	Finland	Large Company	3D-printed textiles
Pentagon Plastics Prototyping	United Kingdom	SME	Metal AM for injection Molding
PEP – Pole Européen Plasturgie	France	RTO	Metal AM for injection Molding
PepsiCo	United States of America	Large company	3D-printed confectionery
Phenix (part of 3Dsystems)	France (United States)	SME	Spare parts for machines Inert and hard implants Surgical planning

Philips	Netherlands	Large Company	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others, 3D-printed confectionery
Philips research Laboratory	United Kingdom	SME	3D-printed textiles
Pia Hinze	Germany	SME	3D-printed textiles
Picanol	Belgium	Large Company	Spare parts for machines
Pininfarina	Italy	Large Company	Plastic-based car interior components
Pinshape	Canda, United States	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Pixologic	United States	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Plansee	Austria	Large Company	Metal AM for injection Molding
Plastic2Print	Netherlands	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others, 3D-printed textiles
Politecnico di Milano	Italy	RTO	Metallic structural parts for airplane
Politronica Inkjet Printing S.r.l.	Torino, Italy	SME	3D-printed textiles
Polyshape	France	SME	Metallic structural parts for airplane
Ponoko	United States, New Zealand	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Porsche	Germany	Large Company	Plastic-based car interior components
Pratt & Whitney	United States of America	Large Company	Metallic structural parts for airplane Spare parts for machines
Print Cheese	Netherlands	SME	3D-printed confectionery
Print2Taste Bocusini	Germany	SME	3D-printed confectionery
Printelize	Poland	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Product Engineering, Machine Design and Automation (PMA) division of KU Leuven[834]	Belgium	RTO	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Prodways (part of Group-Gorgé)	France	SME	Inert and hard implants and Surgical planning
Profactor	Austria	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others

[834] collaborating with Materialse as industrial partner

Protolabs (including Alfaform, recently absorbed)	United States of America	Large Company	Plastic-based car interior components, Metal AM for injection Molding
Protoshop	Finland	SME	Plastic-based car interior components
PSA - Peugeot Citroën	France	Large Company	Plastic-based car interior components
Purmundus	Germany	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Putzmeister UK Ltd	Germany		Affordable Houses
PV Nano Cell	Israel	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Queensland university of Technology (Brisbane)	Australia	RTO	Surgical planning Inert and hard implants
Rapid 3D	South Africa	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Rapid Technology Center (RTC) at the University of Duisburg–Essen	Germany	RTO	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Realizer	Germany		Spare parts for machines
Recreus	Spain	SME	3D-printed textiles
Reimagine Food	Spain	SME	3D-printed confectionery
Renault - Nissan	France	Large Company	Metal AM for injection Molding Plastic-based car interior components
Renishaw	United Kingdom	Large Company	Metallic structural parts for airplane Metal AM for injection Molding Spare parts for machines Inert and hard implants Surgical planning
RepRap	United Kingdom	Non-profit; SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others, 3D-printed textiles
RICO Auto Industries	India	Large Company	Plastic-based car interior components
ROB Technologies AG	Switzerland	SME (ETHZ spin-off)	Affordable Houses
Robots in Gastronomy (RIG)	Spain	SME	3D-printed confectionery
ROHACO	Netherlands	Large company	Affordable Houses
Rolls Royce	United Kingdom	Large Company	Metallic structural parts for airplane Plastic-based car interior components
Rowenta	Germany	Large Company	Metal AM for injection Molding
Rudenko	United States of America	SME	Affordable Houses
RWTH Aachen University	Germany	RTO	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Sabin Design Lab	United States of America	SME	Affordable Houses
Sächsisches Textilforschungsinstitut e.V. (STFI)	Germany	RTO	3D-printed textiles

SAFRAN (incl. SNECMA and Techspace Aero)	France	Large Company	Metallic structural parts for airplane
Saint Gobain	France	Large company	Affordable Houses
Sandvick Coromant	Sweden	Large Company	Spare parts for machines
Sandvik	Sweden	Large Company	Metal AM for injection Molding Metallic structural parts for airplane
Sandvik Mining and Construction Ltd	Finland	Large Company	Spare parts for machines
Saxion University of Applied Sciences	Netherlands	RTO	3D-printed textiles
Schneider	Germany	Large Company	Metal AM for injection Molding
Schunk	Germany	Large Company	Spare parts for machines
Science and Technology Facilities Council	United Kingdom	RTO	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Sculpteo	France	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
SECO Tools	Sweden	Large Company	Spare parts for machines
Shape and form	Germany	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Shapeways	United States of America	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others 3D-printed textiles
Shapify	United States		Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Shotcrete Services Ltd	United Kingdom	SME	Affordable Houses
Siemens	Germany	Large Company	Plastic-based car interior components
Siemens	Netherlands	Large Company	Spare parts for machines
Siemens Healthcare	Germany	Large Company	Surgical planning Inert and hard implants
Sikorsky	Poland	Large Company	Metallic structural parts for airplane
Simpleware	United Kingdom	Large Company	Metallic structural parts for airplane
Singapore Centre for 3D-printing	Singapore	RTO	Affordable Houses
Sintef	Norway	RTO	Metal AM for injection Molding
SIRRIS	Belgium	RTO	Inert and hard implants Surgical planning
Skanska	Sweden	Large company	Affordable Houses
SLM Solutions Group AG	Germany	Large Company	Metallic structural parts for airplane, Plastic-based car interior components Metal AM for injection Molding Spare parts for machines Inert and hard implants Surgical planning Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others

Smith and Nephew	United States	Large Company	Inert and hard implants Surgical planning
Sokaris	France	SME	Metallic structural parts for airplane
Sols	United States of America	SME	3D-printed textiles
Somos (DSM)	Netherlands	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
SP Processum AB	Sweden	Initative (60% RTO owned, 40% company owned)	Affordable Houses
Spa Monopole	Belgium	Large Company	3D-printed confectionery
Spark by Autodesk	United States	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Spartacus 3D	France	SME	Metallic structural parts for airplane
Spritzguss + Formenbau Bergmann	Germany	SME	Metal AM for injection Molding
Staramba	Germany	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Stratasys	United States	Large Company	Metallic structural parts for airplane Plastic-based car interior components Metal AM for injection Molding Spare parts for machines Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others Inert and hard implants Surgical planning
Stryker	United States	Large Company	Inert and hard implants Surgical planning
Systems and Materials Research Consultancy of Austin	United States of America		3D-printed confectionery
Tamicare	United Kingdom	SME	3D-printed textiles
Tampere University of Technology	Finland	RTO	3D-printed textiles Inert and hard implants Surgical planning
Technical University Hamburg-Harburg (TUHH)	Germany	RTO	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Technical University of Cluj-Napoca	Romania	RTO	Surgical planning Inert and hard implants
Technological Centre for Mouldmaking, Special Tooling and Plastic Industries (CENTIMFE)	Portugal	RTO	Metal AM for injection Molding
Teilefabrik by Alphacam	Germany	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others

Tenecco	United States	Large Company	Plastic-based car interior components
Tesla	United States	Large Company	Plastic-based car interior components
Tetrapack	Sweden	Large Company	Spare parts for machines
Textilforschungsinstitut Thüringen-Vogtland e.V.	Germany	RTO	3D-printed textiles
the Choc Creator by Choc Edge	United Kingdom	SME	3D-printed confectionery
the Foodini by Natural Machines	Spain	SME	3D-printed confectionery
The Interactive Institute Swedish ICT	Sweden	RTO	Affordable Houses
The Rapid Manufacturing Research Group, Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University,	United Kingdom	RTO	3D-printed textiles
The von Karman Institute for Fluid Dynamics	Belgium	RTO	Metal AM for injection Molding
Thingiverse by Makerbot	United States	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Tiger	Austria	Large Company	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
TLS	Germany	SME	Metallic structural parts for airplane Metal AM for injection Molding
TNO	Netherlands	RTO	Metallic structural parts for airplane Metal AM for injection Molding Spare parts for machines Affordable Houses 3D-printed confectionery
Trumpf	Germany	Large Company	Plastic-based car interior components Metal AM for injection Molding Spare parts for machines
TWI	United Kingdom	RTO	Metallic structural parts for airplane
TWINKIND 3D	Germany	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
UC Berkeley's College of Environmental Design	United States of America	RTO	Affordable Houses
Ultimaker	Netherlands	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others Affordable Houses
Umeå University	Sweden	RTO	Affordable Houses
UNIBO – University of Bologna	Italy	RTO	Metallic structural parts for airplane Plastic-based car interior components
Unilever	United Kingdom	Large Company	Metal AM for injection Molding
Univeristy of Padua	Italy	RTO	Metallic structural parts for airplane

University Bolton	United Kingdom	RTO	3D-printed textiles
University of Cranfield	United Kingdom	RTO	Metallic structural parts for airplane
University of Düsseldorf	Germany	RTO	Metal AM for injection Molding Plastic-based car interior components
University of Freiburg	Germany	RTO	Metal AM for injection Molding
University of Hamburg	Germany	RTO	Plastic-based car interior components
University of Leuven	Belgium	RTO	3D-printed confectionery
University of Liverpool	United Kingdom	RTO	Surgical planning Inert and hard implants
University of Michigan	United States	RTO	Inert and hard implants
University of Milan	Italy	RTO	Plastic-based car interior components
University of Munich	Germany	RTO	Metal AM for injection Molding
University of Nottingham (Additive Manufacturing and 3D-printing Research Group)	United Kingdom	RTO	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
University of Padua	Italy	RTO	Plastic-based car interior components
University of Pisa	Italy	RTO	3D-printed confectionery
University of Salerno	Italy	RTO	Metallic structural parts for airplane Plastic-based car interior components
University of Sheffield	United Kingdom	RTO	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others Metallic structural parts for airplane
University of Southampton	United Kingdom	RTO	3D-printed textiles
University of Zurich	Switzerland	RTO	Metal AM for injection Molding
UP3D.com	China	SME	3D-printed textiles
US Government (Federal Departments: DoD, NASA)	United States of America	Public Entity	Spare parts for machines
UTBM	France	RTO	Metallic structural parts for airplane
UTC	France	RTO	Metallic structural parts for airplane
Valeo	France	Large Company	Plastic-based car interior components
Valimet	United States of America	SME	Metallic structural parts for airplane
VirtuMake/fabberlounge /3dcopy systems GmbH	Austria	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Visage Imaging	Australia	SME	Surgical planning Inert and hard implants
Volkswagen	Germany	Large Company	Plastic-based car interior components
Volvo	Sweden	Large Company	Plastic-based car interior components
VoxelJet	Germany	SME	Metallic structural parts for airplane, Metal AM for injection Molding, Lighting and other home decoration products, such as furniture, vessels (vases,

			bowls, cups etc.), sculptures, and others Affordable Houses
VTT Technical Research Centre of Finland	Finland	RTO	Metal AM for injection Molding Spare parts for machines 3D-printed confectionery 3D-printed textiles
Wageningen University, Laboratory of Food Process Engineering	Netherlands	RTO	3D-printed confectionery
Wärtsilä	Finland	Large Company	Spare parts for machines
Warwick University	United Kingdom	RTO	Inert and hard implants
Wearable Technology Ltd.	United Kingdom	SME	3D-printed textiles
Weber Building Solutions (part of Saint Gobain)	France	Large company	Affordable Houses
Weihenstephan-Triesdorf University of applied sciences (Institute for Food Technology)	Germany	RTO	3D-printed confectionery
White Architects	Sweden	SME	Affordable Houses
WinSun Decoration Design Engineering Co. (Yingchuang)	China	SME	Affordable Houses
WithinLab (now part of Autodesk)	United States of America	SME	Affordable Houses
Xilloc	The Netherlands	SME	Inert and hard implants Surgical planning
XYZprinting	Taiwan	Large company	3D-printed confectionery
YANFENG	Japan	Large Company	Plastic-based car interior components
Z Corp (originated from MIT, now part of 3D Systems)	USA	Large company	Affordable Houses
ZERA	Germany	SME	Plastic-based car interior components
Zodiac Aéro	France	Large Company	Metallic structural parts for airplane
Zortrax	Poland	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Z-Werkzeugbau Gmbh	Austria	SME	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others

14/ List of interviewees

Name	Position	Organisation	Date of interview	Main field of expertise
Adam Moroz	Senior Research Fellow at Additive Manufacturing Technology Groupb	De Montfort University (Leicester)	28/01/2016	Inert and hard implants
Alberto Leardini	Technical director Movement analysis laboratory and functional-clinical evaluation of prostheses	Instituto Orthopedico Rizzoli di Bologna	30/12/2015	Surgical planning
Alessandro Fassi	Founder	Fassi and Associated	Validation	Food and Construction
Alessandro Fortunato	Assistant Professor	Univeristy of Bologna	23/11/2015	Plastic-based car interior components
Alexandre Faure	Customer Relation Specialist	EOS	07/01/2016	Metal AM for injection Molding
Ali Harlin/ Heikkilä Pirjo	Research Professor	VTT Technical Research Centre of Finland	13/11/2015 and 22/12/2015	3D-printed textiles
Alma Krug	Business development manager	Heijmans (NL)	26/01/2015	Affordable Houses
Andreas Schwirtz	Director	VirtuMake GmbH	14/01/2016	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Andy Cooper	Science impact Leader	AG research New Zealand	13/11/2015	3D-printed textiles
Anita Fuchsbauer, DI, Dr.	Employee, Project Coordinator DIMAP	Profactor GmbH	28/01/16	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Antonio Alvigini	Engineer, Owner	Studio di ingegneria Alvigini-Mendolicchio	Validation	Food and Construction
Arto Koivuharju	CEO	Fimatec (FI)	03/02/2016	Affordable Houses
Aziz Huskic, Prof. (FH) Dr.-Ing.	Professor	Center for Smart Manufacturing (CSM) at Upper Austria University of Applied Sciences	25/01/16	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Bart van de Schueren	Vice President Industrial Production	Materialise	25/11/2015	Plastic-based car interior components
Benoit Verquin	Pôle 2PI Procédés Performants Innovants	CETIM	18/01/2016	Spare parts for machines
Bernard Cruycke	CEO	Melotte	12/01/2016	Metal AM for injection, Surgical planning and

Name	Position	Organisation	Date of interview	Main field of expertise
				Molding and spare parts for machines
Bernhard Heiden, FH-Prof. Mag. DI Dr.	Professor	FH Carinthia, SmartLabs Carinthia	25/01/16	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Bernhard Wiedemann	Network coordination partner	Automotive-BW	25/11/2015	Plastic-based car interior components
Berta Gonzalvo	Director	Aittip technology centre	19/01/2016	Inert and hard implants
Carsten Engel	CTO	Xilloc	09/02/2016 and 02/06/2016	Inert and hard implants and Surgical Planning
Claude Lory	Director	Cerameurop	27/01/2016	Inert and hard implants
Claus Aumund-Kopp	Project Leader	Fraunhofer IFAM	12/01/2016	Metal AM for injection Molding
Dario Rea	Corporate Innovation Director	IMA	26/01/2016	Spare parts for machines
David Gonzalo Fernandez	Director of Advanced manufacturing	Prodintec	05/02/2016	Inert and hard implants
David Muller	Business Unit Process and Mold Manager	Centre Technique de la Plasturgie et des Composites (PEP)	04/01/2016	Metal AM for injection Molding
David Wimpenny	Chief Technologist – Component Technology	Manufacturing Technology Centre (MTC)	18/12/2015	Metallic structural parts for airplane
Dr. Markus Rechlin and Hans J. Ihde	CEO and Chairman of supervisory board & founder of the company	SLM Solutions	04/02/2016	Spare parts for machines
Dr. Pieter Verboven	Industrial Research Manager in Division of MeBioS	University of Leuven	Phone interview 3/2/2016	3D-printed confectionery
Emanuele Pensavalle	Head of Program Office	AvioSpace	13/01/2016	Metallic structural parts for airplane
Florence Clément	Bureau Member	CNES	13/01/2016	Metallic structural parts for airplane
Florent Adeline	Marketing Director	Peugeot	20/11/2015	Plastic-based car interior components
Ger Brinks	professor at research group Smart Functional Materials	Saxion University of Applied Sciences; director of BMA Techne	11/01/2016	3D-printed textiles
Greg Gibbons	Head of WMG's Additive Layer Manufacturing group	Warwick University	18/01/2016	Metallic structural parts for airplane and Surgical planning
Gregor Zimmermann	CEO and founder	G.tecz Engineering	Validation	Food and Construction
Henriette Bier	Assistant Professor	TU Delft (NL)	22/01/2016	Affordable Houses

Name	Position	Organisation	Date of interview	Main field of expertise
Ingo Ederer and Daniel Günther	CEO and Director R&D	Voxeljet AG	22/01/2016	Metal AM for injection Molding and spare parts for machines
Jacopo Testa	Founder	Patdesign	Validation	Food and Construction
Jan Ågren	Senior Manager Cockpit & Surface Materials	Volvo Cars	30/11/2015	Plastic-based car interior components
Jean Marc Sanguesa	Gérant	DPH International	07/01/2016	Metal AM for injection Molding
Jean-Yves Ferré	SolidWorks Technical Director	Dassault Systèmes	20/11/2015	Plastic-based car interior components and Metal AM for injection Molding
Jez Clements	Partner	Cambridge Design Partnership	30/11/2015	Plastic-based car interior components
Jim Kor	President	KOR EcoLogic Inc.	24/11/2015	Plastic-based car interior components
Johannes Gartner	Director	Dannes Solutions GmbH	18/01/2016	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Jonas Van Vaerenbergh	(co-)Founder	Layerwise	15/01/2016	Metallic structural parts for airplane
Josef Kurz & Pieter Vos	Marketing Coordinator	Materialize Austria & Belgium	04/01/2016	3D-printed textiles
Jukka Tuomi	Research Director; President of the Finnish Rapid Prototyping Association FIRPA	Aalto University / Finnish Rapid Prototyping Association	Phone interview 1/2/2016	3D-printed confectionery
Jürgen Stampfl, ao.Univ.Prof. Dipl.-Ing. Dr. mont.	Professor	University of Technology Vienna, Inst. of Materials Science and Technology	25/01/2016	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Jussi Loponen	Head of Research	Fazer Group	Phone interview 21/01/2016	3D-printed confectionery
Karen Deleersnyder	Scientist	Centexbel Ghent	08/01/2016	3D-printed textiles
Karl Hewson	Design Engineer	Cambridge Design Partnership	26/11/2015	Plastic-based car interior components
Kenneth Delgarno	Sir James Woodeson Professor of Manufacturing Engineering	NewCastle University School of Mechanical and Systems Engineerding	08/01/2016	Inert and hard implants

Name	Position	Organisation	Date of interview	Main field of expertise
Kjeld van Bommel	Senior consultant in 3D-printing of food,	TNO	Phone interview 14/12/2015	3D-printed confectionery
Klas Boivie	Senior Research Scientist.	SINTEF	11/01/2016	
Klas Boivie	Research Scientist	Sintef	11/01/2016	Metal AM for injection Molding and spare parts for machines, Metallic structural parts for airplane and Spare parts for machines
Linda Nyström	3DP project manager	Umeå University (SE)	11/01/2016	Affordable Houses
Linnéa Dimitriou	Creative director of Slipertiet	Umeå University (SE)	11/01/2016	Affordable Houses
Luca Alessandro Fortunato and Luca Tomesani	Director and Researcher	Centro Interdipartimentale di Ricerca Industriale su Meccanica Avanzata e Materiali, Univeristy of Bologna (UNIBO)	23/11/2016	Metallic structural parts for airplane and Plastic-based car interior components
Maarten Schutyser (dr. ir.)	Ass. Professor in Food Process Engineering	Wageningen University, Laboratory of Food Process Engineering	Phone interview 1/2/2016	3D-printed confectionery
Marc de Smit	R&D Engineer	NLR	15/12/2015	Metallic structural parts for airplane
Martin Ruff	Team Leader	DLR	23/11/2015	Metallic structural parts for airplane and Plastic-based car interior components
Mateusz Sidorowicz	Sales Manager	3D Genre	12/04/2016	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Matteo Attrovio	CIO	Finmeccanica	08/01/2016	Metallic structural parts for airplane
Melissa C. Sharp	Business Development Coordinator	NC State University	13/11/2015	3D-printed textiles
Mika Salmi	Project manager/postdoc researcher	Aalto University, department of Engineering Design and Production	14/01/2016	Inert and hard implants
Mirko Bromberger	Director Marketing & Additive Manufacturing Strategy	ALTAIR	22/12/2015	Metallic structural parts for airplane
Nadav Sella	Director, Manufacturing Tools, Vertical Solutions	Stratasys	30/12/2016	Metal AM for injection Molding
Neil Burns and Louise Geekie	Co-Director (founder) and Project Director	CROFT Additive Manufacturing	08/01/2016	Metal AM for injection Molding
Nesli Sözer	Research Scientist	VTT	Meeting 27/11/2015	3D-printed confectionery

Name	Position	Organisation	Date of interview	Main field of expertise
Ola Harrysson	Professor and Fitts Fellow	North Carolina State University	28/01/2016	Spare parts for machines
Olaf Andersen	Head of Department	Fraunhofer IFAM	11/01/2016	Metal AM for injection Molding and spare parts for machines
Olaf Bieddermann	Programme development leader	Faurecia	20/11/2015	Plastic-based car interior components
Oliver Tessmann	Professor	Technical University Darmstadt (DE)	22/01/2016	Affordable Houses
Olivier Strebelle	Deputy CEO in charge of Strategy and Business development	Groupe Gorgé	28/01/2016	Spare parts for machines, Inert and hard implants and Surgical planning
Onno Ponfort	Practice Leader 3D-printing	Berenschot	14/01/2016	Spare parts for machines
Paolo Fino	Professor	Politecnico di Milano	22/01/2016	Metallic structural parts for airplane
Pasi Puukko	Research Team Leader	VTT	Validation	Food and Construction
Patrick Ohldin	Sales Manager	Arcam	18/01/2016	Metallic structural parts for airplane and Inert and hard implants
Paul Kiekens/ Lieva Van Langenhove	Professors at Department of Textiles	Ghent University	13/11/2015	3D-printed textiles
Peter Mercelis	Director Applied Technologies, Healthcare at 3D Systems Corporation	Layerwise (3Dsystems)	15/01/2016	Inert and hard implants
Pieter Vos	Marketing Coordinator	Materialise NV	19/01/2016 and 02/02/2016	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Ralf Schumacher	Head Group for Medical additive manufacturing	University of applied Sciences	13/01/2016 and 10/05/2016	Inert and hard implants and Surgical planning
Reinhold Schneider	Scientist	ITCF Institut für Textilchemie und Chemiefaser Denkendorf	13/11/2015	3D-printed textiles
René Jähne	Knowledge and Technology Transfer, NCCR Digital Fabrication	ETH Zürich (CH)	22/01/2016	Affordable Houses
Rob Francis	Director of Innovation and Business Improvement	SKANSKA (SE/UK)	25/01/2016	Affordable Houses
Roya Ashayer-Soltani	Materialise	NPl National Physical Laboratory	13/11/2015	3D-printed textiles

Name	Position	Organisation	Date of interview	Main field of expertise
Ruben Heid and Christopher Thoma	Technologieentwicklung Giessen	AUDI AG	15/01/2016	Metallic structural parts for airplane
Russell Harris	Professor	University of Leeds	02/06/2016	Mechanical Engineering
Sabine Gimpel	Scientific Marketing	Textilforschungsinstitut Thüringen-Vogtland e.V.	12/01/2016	3D-printed textiles
Sarah Lysann Göbel / Frank Siegel	Scientists	Sächsisches Textilforschungsinstitut e.V. (STFI)	14/01/2016	3D-printed textiles
Sébastien Pillot	R&D Engineer	CETIM	27/01/2016	Metallic structural parts for airplane
Søren Møller Parmar-Sielemann	Senior Consulent	Welfare Tech Patient@home	13/01/2016	Surgical planning
Stewart Williams	Director of the Welding Engineering and Laser Processing Centre	Cranfield University	07/01/2016	Metallic structural parts for airplane
Sylvain Charpiot	CEO	Drawn	12/04/2016	Furniture
Theo Salet	Professor	TU Eindhoven (NL)	19/12/2015	Affordable Houses
Thierry Dormal	Program Manager Additive Manufacturing	SIRRIS	18/01/2016	Metal AM for injection Molding , Inert and hard implants, and Surgical planning
Thierry Lavigne	Directeur Technique	Sokaris	27/11/2015	Metallic structural parts for airplane
Thomas Köpplmayr, DI, Dr.	Employee	Profactor GmbH	28/01/16	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Thomas Pletsch	Network coordination partner	Automotive-BW	25/11/2015	Plastic-based car interior components
Tim Geurtjens	CTO	MX3D (NL)	20/01/2016	Affordable Houses
Ulli Klenk	General Manager Competence Center Additive Manufacturing	Siemens	20/01/2016	Spare parts for machines
Wieland Schmidt, Dipl. Ing. Architect	Architect/CEO	Shape and Form	12/04/2016	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Wolfgang Trümper	R&D Manager at Institute of Textile Machinery & High Performance Material	Technische Universität Dresden	13/11/2015	3D-printed textiles

Name	Position	Organisation	Date of interview	Main field of expertise
Zoltan Major, Prof. Dr.	Professor	Johannes Kepler University Linz	28/01/16	Lighting and other home decoration products, such as furniture, vessels (vases, bowls, cups etc.), sculptures, and others
Andrea Giorgis	Managing Director & International Sales Manager	Omes srl	Written feedback	Mechanical
Davide Sher	CEO	3dprintingbusiness directory	Written feedback	Services
Paolo Buzzetti	Managing Director	Gravures Buzzetti srl	Written feedback	Mechanical
Thomas Baldi	Managing Director	Modello Glacière S.p.r.l	Written feedback	Services/lighting
Paolo Calefati	Innovation Manager	Prima Industrie SpA	Written feedback	Mechanical
Jacopo Testa	Associate	Patdesign	Written feedback	Construction
Rene Varek	Member of the Board / Chief Operating Officer	Amserv	Written feedback	Automotive
Federico Bertoni	Business development, sales manager*	Injecta srl	Written feedback	Mechanical
Antonio Alvigini	Associate	Alvigini -Mendolicchio	Written feedback	Construction
Alessandro Fassi	Associate	Fassi and Associates	Written feedback	Construction
Alexis Moreau	Ceo	SIB Tech Orthodontics	Written feedback	Medical
Beatrice Alfonso	Marketing and sales department*	Herniamesh srl	Written feedback	Medical
Ruth Goodridge	Assistant Professor in Additive Manufacturing & 3D Printing	University of Nottingham	19/04/2016	Medical
Ron Scerri	Country manager	House of Fashion – Camilleri Holdings	Written feedback	Textile/Fashion
Maicol Urbinati	Owner	MakeRN Association	Written feedback	Services/Fablab
*	Please note that these interviewees asked to indicate the following disclaimer ***NOTE: The above written words are just my personal opinion, as a person, so they cannot be considered as an official belief of the Company I work for.***			

EA-01-16-676-EN-N

ISBN 978-92-9202-202-0