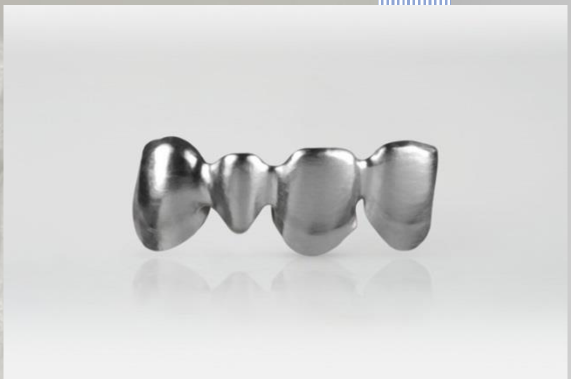
2014

Additive Manufacturing:
Strategic Research Agenda



AM SRA Final Document

PLATFORM

AM SRA Final Document

EXECUTIVE SUMMARY

BACKGROUND

This Strategic Research Agenda (SRA) has been produced by the AM Sub-Platform as an update to the previous strategy documents produced. It also aims to highlight the priority areas for future development in and across the Additive Manufacturing (AM) landscape.

MANUFACTURING

Manufacturing has been highlighted by the European Union (EU) as one of the key enablers to tackling some of the European challenges and their subsequent targets, in particular for growth and creating high quality value-adding jobs. The Horizon 2020 Framework Programme is taking action to support and promote business research and innovation in enabling technologies. One of the priority actions will cover advanced manufacturing and processes (Domain 1 of the Factories of the Future Multi-annual Roadmap (EFFRA, 27 November 2012)).

MANUFUTURE launched the European 'Factories of the Future Research Association (EFFRA) in 2009 with the objective to encourage pre-competitive research on production technologies within the European Research Area. This was to be achieved through engagement with the ‘Factories of the Future’ (FoF) Public-Private Partnership (PPP) with the EU (Bessey, 15 May 2012).

FoF has developed a roadmap for 'Factories of the Future 2020' (EFFRA, 27 November 2012). This roadmap highlights AM as a ‘key advanced manufacturing process’ and one where a broad range of benefits can be realised, including its potential for supporting environmental sustainability for manufacturing.

INVESTMENT

The AM profile has been significantly raised in more recent years. Its identification as a ‘high value’ and ‘advanced’ manufacturing technology have facilitated a number of regional AM focused funding initiatives and project based research across the globe. Having said this, the European Framework funding programme has supported the development of projects covering AM based-research since 2008.

The US is following the European lead and is currently exerting efforts by the launch of the National Additive Manufacturing Innovation Institute (NAMII), with the aim of mainstreaming AM within industry in order to boost the manufacturing economy within the US. They are reporting an almost $40 million industry match to the $30 million federal investment.

STANDARDS

The AM industry is starting to respond to the needs for standardisation on a global, national and regional level and a number of committee forums, with substantial European Involvement have been created such as:

- ASTM F432 Committee
- ISO Technical Committee (TC 261)
- SASAM Project
- BSI Committee

DEFINITION AND PROCESS TERMINOLOGY

The ASTM has defined 'Additive Manufacturing' as a (ASTM International, 2012):

"process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining."

AM processes can be categorised by the type of material used, the deposition technique or by the way the material is fused or solidified. Process terminology is being defined by the ASTM F42 committee. The processes have been categorised into seven areas as follows:

1. Vat Photopolymerisation
2. Material Jetting
3. Binder Jetting
4. Material Extrusion
5. Powder Bed Fusion
6. Sheet Lamination
7. Directed Energy Deposition

READINESS LEVELS

To gauge the current manufacturing maturity of AM it is useful to measure AM applications against the Technology Readiness Level (TRL) scale. Following initial development from NASA, other organisations and industry have widely accepted the TRL scale as a way of measuring the maturity of the application of a technology.

MARKETS

The AM industry is expected to continue strong growth over the next few years, it was estimated at $1.7 billion for 2011, by 2015 the sale of AM products and services is predicted to reach $3.7 billion worldwide. In terms of AM machines, the plastics market is leading AM and currently there are around 30,000 machines in the field. There is also potential growth for metallic AM, as the metal parts market has over 500 machines sold to date (Wohlers, 2012) and despite the global recession, it is expected that metal AM machines will see double digit percentage increased growth in sales over the next five years.

In terms of industry specific, AM has flourished considerably in the last few years in particular areas. However, there are two distinct markets which are slowly developing products made by AM; one is the industrial/production market, which includes medical, (orthopaedic implants) dental, aerospace, automotive and power generation. The other is the consumer market which includes home accessories, fashion and entertainment. Within these sectors, AM has provided benefits including design freedom, reduced time to market in product development, service and increased R&D efficiency.

RECOMMENDATIONS

The following is a summary of the recommendations serviced from the SRA generation process:

TECHNICAL AM DEVELOPMENT	
Productivity	
Increase build-speed, possibly through new approaches to scanning or sources of energy.	Decrease the time to create each layer, the overall time between layers, and start-up and shut-down time.
Support higher volume production, possibly through enabling batch consistency and methodologies for consistent materials supply.	Develop methodologies for measurement of AM products.
The development of new/advanced AM machines e.g. machines with multiple lasers.	
Materials	
Develop AM materials performance, static and fatigue, to enable a similar or superior demonstrable performance level of cast and wrought material.	Develop materials' consistency and repeatability e.g. fixing process parameters.
Interchange-ability of process parameters between different AM machines.	Analyse material properties of different materials and multi-materials using AM techniques, including their validation.
Identification of new semi-crystalline and amorphous polymers suited to different AM mechanisms.	Analyse and develop of new materials for AM processing e.g. biomaterials, superconductors and new magnetic materials, high performance metal alloys, amorphous metals, ultra-high temperature ceramic composites, metal-organic frameworks, new nano-particulate and nano-fibre materials.
Tailored materials for AM.	Improve material utilisation.

Process and Stability	
Increase material processability, quality and performance.	Develop methodologies for ‘Right first time’ processing.
Increase control of process tolerances.	Develop tools for better temperature management during processing.
Improve surface finish of processed parts.	Improve geometrical stability.
Improve process control and monitoring.	Analyse energy consumption and development of methodologies for its reduction.
Further develop lasers with improved efficiency and control.	Develop multi-material manufacturing for AM technologies.
Reduce residual stresses.	Increase software utilisation.
Reduce scrap and improve repeatability.	Faster turnaround addressing material/part/component handling.
Materials processing whereby new powder production sources or new/improved methodologies for supply chain integration are facilitated.	Identification of new supply chain opportunities and establishment of existing supply chains for potential products.
Analyse stability of the AM process in order to make improvements to AM systems that will allow production components to be produced with required properties.	
Product Quality	
Develop in-process monitoring and control methodologies and systems including techniques for reducing the requirements for post-processing activities.	Investigate in-situ sensors to provide non-destructive evaluation and allow for early detection of flaws/defects.
Develop a 'streamlined' workflow for hybrid manufacturing, combining AM processes to meet geometric and surface finish requirements.	Develop design tools and methodologies to empower design engineers to take advantage of AM.
Develop material characteristics and the mechanism by which the material is processed to improve surface quality.	Increase the understanding of power-beam manipulation (laser or electron beam) and material interaction(s) and their associated changes particularly for smaller parts production for increased surface finish.
Develop databases to allow a catalogue of materials performance information for particular applications, materials and processes.	Develop an ‘online’ portal of materials information for comparison and sharing.

Economic, Social and Environmental Challenges	
Environment	
Improve the heat sources used in AM, for example more electrically efficient lasers.	Improve process productivity to reduce resource usage including in-process losses.
Validation and standardisation of the batch-to-batch recycling of materials, especially for polymeric materials.	Develop strategies for recycling material after the part has finished its natural usage life e.g. melting of used parts, the monitoring and control of material chemistry, and the atomisation of material to create feedstock for AM systems.
Standards and Certification	
Develop processes to increase certification of AM e.g. advanced in-process inspection and quality control techniques.	Further industry engagement in the ASTM F42, BSI and ISO working groups on standards development.
Develop methodologies for preventing or correcting product defects.	The following topics have been identified as a priority by ISO and ASTM: Qualification and certification methods, design guidelines, test methods for characteristics of raw materials, material recycling guidelines, standard protocols for round robin testing, standard test artefact, requirements for purchased AM parts, harmonization of existing ISO/ASTM terminology Standards, tests on finished parts.
Technology and research requirements need to be categorised as to fit the diverse range of AM technologies, especially for standardisation, liability and intellectual property.	An industry advisory group that focuses on AM supply chains and common areas of capabilities for Europe.
Develop new business models stating clear rules and guidelines on the effective supply of AM produced components to ensure product safety, but also accountability in the event of faulty or damaged parts/products.	
Training and Education	
Develop AM specific training modules encompassing design/ modelling, processes, materials and applications.	Non-technical outreach programmes for management, or other non-technical business personnel, on logistics, lean manufacturing and new business models.
University and technical college courses, education materials, and curricula at basic undergraduate and post-graduate levels.	Events based on specific industrial case studies, technology transfer support and supply chain assistance.
Training programs for industry practitioners certified by professional bodies.	More educational resources dedicated to increasing the knowledge of AM technologies, materials and their applications.

Other	
Global collaboration in the area of AM would be beneficial particularly between EU and USA.	Identification of applications and work with end-users to understand the business case for using AM over other manufacturing routes.
Mechanisms for taking a product into production e.g. taking proven concepts at TRL 4 and moving them to TRL 7 to 9.	Supply chain development, from material supply, reliable AM systems to post-processing.
Functionally graded structures in terms of design or material.	More consideration to the value proposition for AM e.g. digital data.
The creation of assemblies using AM.	Establishment of bio-tissue engineering using AM.

CONTENTS

BACKGROUND

SRA Purpose

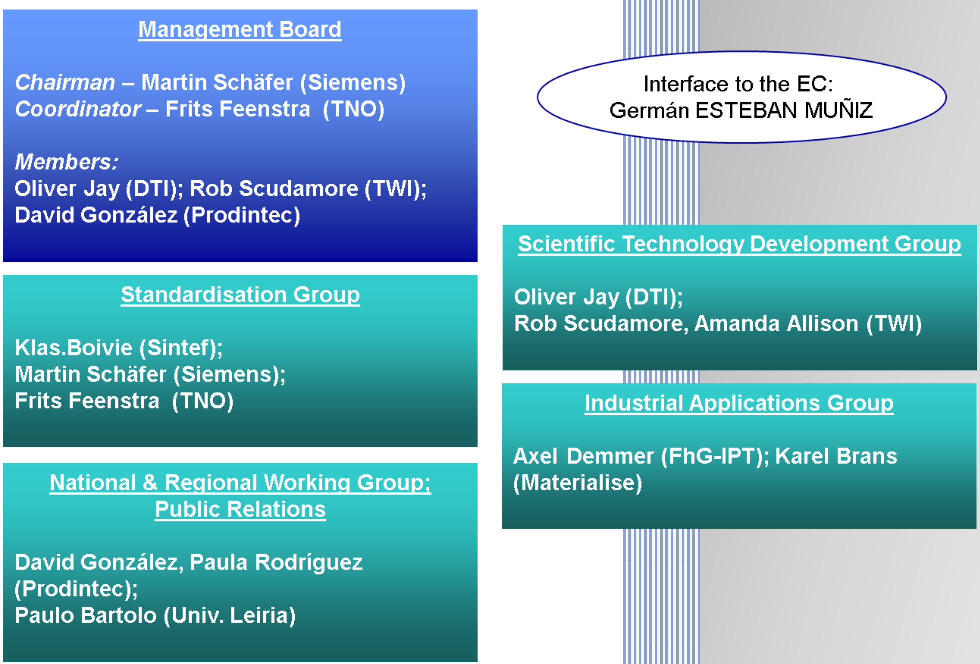
This Strategic Research Agenda (SRA) has been produced by the AM Sub-Platform as an update to the previous strategy documents produced. It also aims to highlight the priority areas for future development in and across the Additive Manufacturing (AM) landscape.

This SRA has been produced in consultation with a number of industry and academic experts within the field of AM. A large amount of information has been sourced from recent research on the subject and from literature that has been concentrated around the European Agenda for industry and manufacturing, as well as global initiatives.

AM Platform

The AM Sub-Platform, initiated by the MANUFUTURE Technology Platform (Manufuture (CNR-ITIA), 2004), acts as a focal point, where key stakeholders in the field, propose and develop activities for increasing the competitiveness of AM. Through this, the AM Sub-Platform continuously engages within the field of AM to ensure its maximum exploitation. This is to ensure that the direction in which AM is landscaping fulfils the requirements and expectations of not only consumers and industry, but also inspects deeper by looking to support the top level European challenges.

The governing structure of the AM Sub-Platform has been organised in a way as to optimise the input and impact of the platform's activities, see image below. The sub-platform interfaces with the EC to ensure relevance on a European and Policy level.



The AM platform holds regular meetings with its Members/Stakeholders, at least once a year, and since its initiation the following meetings have taken place:

Meeting No.	Date	Venue
13th	7 November 2013	TNO, Eindhoven
12th	13 June 2013	EC, Brussels
11th	15 January 2013	EC, Brussels
10th	28 September 2011	VRAP conference, Leiria Portugal
9th	21 June 2011	Ecole Centrale Paris and AFPR Paris
8th	29 June 2010	EC Brussels
7th	6 October 2009	VRAP Leiria Portugal
6th	2 June 2009	EC Brussels
5th	16 September 2008	University of Ljubljana, Slovenia
4th	16 April 2008	Prodintec, Asturias, Spain
3rd	25 September 2007	TCT Conference, Coventry, UK
2nd	14 February 2007	EC, Brussels
1st	28 February 2006	Brussels

European Agenda

The European society has been suffering adversity during the Economic Recession and as such the European Union has taken significant steps to address the issues. They are taking measures by implementing a number of large-scale initiatives to boost the economic situation. The European Union's 'Europe 2020' Strategy (European Union, 13 March 2013) is looking to advance the growth of the European economy through smarter, more sustainable and more inclusive means. For this, a number of key topics covering the economic, social and environmental agendas have been identified. These are being supported through the implementation of five large-scale targets in the areas of:

1. Employment
2. Research and development
3. Environment
4. Education
5. Poverty and social exclusion

Manufacturing

Manufacturing has been highlighted by the European Union as one of the key enablers to tackling some of the European challenges and their subsequent targets, in particularly for growth and creating high quality value-adding jobs. 'HORIZON 2020', the Framework Programme for Research and Innovation is proposing (European Commission, 2011) to take action to support and promote business research and innovation in enabling technologies. One of the priority actions will cover advanced manufacturing and processing.

MANUFUTURE, an industry lead initiative, was set up in 2004 to define and implement research and innovation strategies for driving forward and growing the manufacturing output for Europe. MANUFUTURE launched the European Factories of the Future Research Association (EFFRA) in 2009 with the objective to encourage pre-competitive research on production technologies within the European Research Area. This was to be achieved through engagement with the 'Factories of the Future' (FoF) Public-Private Partnership (PPP) with the European Union (Bessey, 15 May 2012).

EFFRA reported, "In order to allow European manufacturing to have a significant impact in addressing major social-driven targets and challenges, an increase in joint government-industry investments on cross-disciplinary manufacturing research is vital" (EFFRA, 27 November 2012). Therefore, a number of objectives, aligned with pursuing the large scale targets, have been set for manufacturing:

Employment: Creating and maintaining jobs within manufacturing

Value added: Increasing the value added created by manufacturing

Environmental impact:

- Reducing emissions, energy consumption, waste generation and the consumption of materials created by manufacturing activities.
- Enabling the manufacture of eco-products and eco-technologies

Social impact: Enhancing the desirability of jobs in manufacturing.

Research and Development: Increasing business research and development spend in manufacturing.

Innovation: Increasing innovation investments and the number of manufacturing enterprises strategically engaged in innovation activities.

Education: Increasing manufacturing employment opportunities for manufacturing engineering graduates, doctorate holders and technicians.

Entrepreneurship: Promoting the creation of technological based companies around manufacturing of innovative products. (EFFRA, 27 November 2012)

The Importance of AM

Benefits

There are a number of advantages and benefits for AM, in summary these include:

- **CAD-to-Part:** AM allows a 3D CAD drawing of a component or shape to be converted directly into a physical part.
- **Design for Customisation:** Using AM allows users to generate parts with greater customisation, with no additional manufacturing costs, such as extra tooling costs.
- **Design for Function:** AM manufacturing allows the user to design for function rather than for manufacture, for example allowing internal features that would be impossible to produce using conventional manufacturing techniques.
- **Design for Light-weighting:** Novel design and flexible manufacturing enable the production of lightweight structures. For example, parts can be made with hollow or complex lattice structures which retain structural strength but with reduced weight.
- **Near Net and Net Shape Manufacturing:** AM enables the direct production of a component to their final (net) shape or with minimal need for additional process steps.
- **Material Utilisation:** AM techniques have the potential to approach zero waste regarding material utilisation. Any scrap powder generated can also be converted into new powder, ready for use again.
- **Less Pollution:** AM techniques do not directly use toxic chemicals in any measurable amount. This is a direct benefit against traditional machining processes for example.
- **Reduced Time-to Market:** While part forming using AM techniques can be slower than traditional manufacturing steps, the ability to consolidate several machining steps into a single manufacturing step, will dramatically reduce overall manufacturing time.

Factories of the Future

Following a European-wide stakeholder consultation process, a “Factories of the Future PPP Strategic Multi-Annual Roadmap 2010-2013” (Ad-hoc Industrial Advisory Group, 2010) was developed in 2010. From this, the ‘Factories of the Future’ PPP launched four calls for proposals within FP7. This resulted in a number of projects being launched. A large number of these projects were able to showcase some of the positive impacts they are achieving at the Workshop on 'Impact of the Factories of the Future PPP' held in Brussels in March 2013. Within the workshop three parallel sessions were held. In one of these, Session 3 for 'High Performance Manufacturing', it was noted that a number of projects were developing AM processes, even when the call topic was not AM specific. This clearly shows that AM can be used as an enabling technology for future developments.

FoF have further developed the 'Factories of the Future PPP Roadmap' for 'Factories of the Future 2020' (EFFRA, 27 November 2012). This roadmap now highlights AM as a ‘key advanced manufacturing process’ and one where a broad range of benefits can be realised, including its potential for creating sustainable high value European based employment, addressing societal issues and for supporting environmental sustainability for manufacturing.

The roadmap talks about using AM for the manufacture of custom made parts and added functionality. Customisation is seen as a major component within high value manufacturing for providing competitive new products and services.

The roadmap also refers to AM as a one of the ways for 'optimising the exploitation of materials in manufacturing processes'. This can be achieved because of the net shape and material utilisation possibilities of AM.

However, it does also highlight a number of areas where AM requires further research and development focus, such as new business models, strategies and product life cycle management and performance. As yet, AM does not have the suitable methodologies in place to fully enable and exploit its true potential on an economic scale.

Examples of AM development initiatives:

United Kingdom

Minister David Willetts announced on 22 October 2012 that some £7 million UK government investment will go towards innovation in AM technologies for Research and Development, Universities and Science. It was quoted that 'AM has the potential to change the face of manufacturing across the globe'. The UK Technology Strategy Board (TSB), along with Engineering and Physical Sciences Research Council (EPSRC), the Arts and Humanities Research Council (AHRC) and the Economic and Social Research Council (ESRC) managed the competition for collaborative Research and Development Projects in AM. (Technology Strategy Board, 29 October 2012).

The AM Special Interests Group (SIG) reported that AM has huge potential to meet future requirements in environmental sustainability; increasing global competitiveness in manufacturing; and allowing the creation of new products and manufacturing processes for new, agile, more cost effective manufacturing processes; and business. The report pays particular attention and importance on raising the technology readiness levels for AM in order to gain widespread commercial exploitation. The key sectors identified for technology adoption were aerospace, medical devices and implants, power generation and the creative industries (Materials KTN, 2012).

Germany

The Direct Manufacturing Research Centre (DMRC), based at the University of Paderborn in Germany was created in 2008 and is a joint industrial and academia centre aiming to advance AM technologies. DMRC and the Germany North-Rhine-Westphalia State have co-invested over 2 Million Euros. An additional 3.4 Million Euros of project funds were provided by the Rhine-Westphalia State to match additional industry funding, which provided an overall budget of approximately 11 Million Euro for the 5 year plan.

As a result, DMRC has conducted research investigating areas of AM and has produced a number of noteworthy reports:

- ‘Thinking ahead the Future of Additive Manufacturing - Analysis of Promising Industries’ (Gausemeier, et al., 2011);

- 'Thinking ahead the Future of Additive Manufacturing – Future Applications' (Gausemeier, et al., 2012);
- 'Thinking ahead the Future of Additive Manufacturing – Innovation Roadmapping of Required Advancements' (Gausemeier, et al., 2013);

These reports target a number of industries identified as 'promising' for AM applications such as those in the areas of aerospace, automotive and electronics.

Research Projects

The European Framework funding programme has already seen considerable support from projects covering AM research and some of these include:

- **OXIGEN – 2013-2017:** Oxide dispersion strengthened materials for the AM of high temperature components in power generation. OXIGEN will develop different (Oxide Dispersion Strengthened (ODS)) alloys individually designed to address specific high temperature materials performance challenges currently limiting power generation component capabilities.

- **AMAZE – 2013-2017:** AM aiming towards zero Waste and efficient production of high-tech metal products. The overarching goal of AMAZE is to rapidly produce large defect-free additively-manufacture metallic components up to 2 metres in size, ideally with close to zero waste. A further aim is to achieve 50% cost reduction for finished parts, compared to traditional processing.

- **CassaMobile – 2013-2016:** Mini-factories for customised products using local flexible production.

- **MANSYS – 2013-2016:** 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.

- **M&M'S+ – 2013-2014:** 3D Printer for silicon MEMS & NEMS. The project will explore ways to develop and commercially exploit a new type of 3D printing tool for manufacturing of silicon nanostructures. These 3D printers will make it possible to design and implement silicon micro- and nano-electromechanical system (MEMS&NEMS) sensors and photonic components.

- **HYPROLINE – 2012-2015**: High performance production line for small series metal parts. The objective of Hyproline is to strengthen the competitiveness of the European industry by introducing manufacturing methods, which will allow companies to reduce time-to-market and number of rejects; make more customised and innovative products; and make products >20% more accurate with considerable savings (>30%) in consumption of waste metal, fluids and services, with an equivalent reduction of CO2 emission.

- **3D-HiPMAS - 2012-2015:** Pilot Factory for 3D High Precision MID Assemblies. The project demonstrates pilot line fabrication of advanced MID based micro assemblies and addresses important branches such as communication, transportation, life sciences and energy.

- **AMCOR – 2012-2015:** AM for wear and corrosion applications. The Project 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 supplied by industry that are subjected to in-service wear and corrosion.

- **HiPr – 2012-2015:** High-Precision micro-forming of complex 3D parts 31. The 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.

- **SASAM – 2012-2014:** Support action for standardisation in AM. SASAM's mission is to drive the growth of AM to efficient and sustainable industrial processes by integrating and coordinating Standardisation activities for Europe by creating and supporting a Standardisation organisation in the field of AM.
- **AEROBEAM 2012-2013:** Direct Manufacturing of stator vanes through electron beam melting. Aerobeam is aimed at increasing the TRL of EBM through investigation of recyclability of EBM powder and the mechanical properties of aeronautical Ti6Al4V stator vanes elaborated by EBM, an AM Technique.

- **NANOMASTER – 2011-2015:** Graphene based thermoplastic master batches for conventional and AM processes. The aims of the project are to reduce the amount of plastic used to make a component.

- **MERLIN – 2011-2014:** Development of Aero Engine Component Manufacture using Laser AM. The concept of the MERLIN project is to reduce the environmental impact of air transport using AM techniques in the manufacture of civil aero engines.

- **HIRESEBM – 2011-2013:** High resolution electron beam melting with the aim of developing an electron beam melting (EBM) AM process to enable the fabrication of high resolution medical implants with optimised porous structures directly from metal powder.

- **ADM-ERA – 2011-2013:** Reinforcing AM 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 CMRDI into the ERA, by developing cooperation with European research and innovation organisations in AM of Ti and CoCr alloys based prostheses, and biocompatible ceramic materials: HA, PEEK and TCP.

- **DIGHIRO – 2010-2014:** Digital Generation of High Resolution Objects. The project will develop a micro scale AM system. The plan is to study many applications of micro scale AM technology, including micro fluid diagnostics (lab-on-the-chip) and medical applications.

- **PHOCAM – 2010-2013:** Photopolymer based customised AM technologies. This project aims at developing integrated lithography-based AM systems which will, for the first time, facilitate the processing of photopolymer-based materials for the factory of the future.

- **KARMA – 2010-2013:** Knowledge based process planning and design for AM. The objective of this project is to design, develop and test an Expert Process Planning tool, implemented into a knowledge-based engineering system (KBE) that can suggest the optimal technological scenario, the optimal build orientation and estimate functional properties of AM parts automatically and in a short time.

- **Step-up – 2009-2012:** Step-up in polymer based RM processes. An innovative mechano-chemical approach (based on high energy ball milling) will be used for the development of innovative nanopolymers to be used in AM based on Selective Laser Sintering (SLS).

- **DirectSpare – 2009-2012:** The project investigated the strengthening of industries competitive position by the development of a logistical and technological system for spare parts that is based on on-demand production.

- **IMPALA – 2008-2012:** The development work within IMPALA focussed on demonstrating significant advantage over conventional manufacture and ensuring further uptake of LAMP processes for the manufacture of medical implants, aero-engine components and other small-size applications in the dental, electronic, (micro-) tooling and precision-mechanics field.

- **CompoLight – 2008-2011:** The project proposed to solve identified shortcomings of AM by addressing five areas, all of which were related to design and production of lightweight metal parts.

The information for these projects where taken from the European Union CORDIS website: http://cordis.europa.eu/ (CORDIS Search Service - European Union, 2013)

Looking at these projects from a top level view it can be noted that important research in the field of AM has been achieved, in particularly for specific AM techniques and focussed applications within the medical and aerospace sectors. Development of standard materials (polymers and metals) for AM manufacture, seem to have a presence, along with some limited scoping for ceramics and new materials. More recently, research is seeing the development of standardisation for the technology and for larger AM part production.

Although the AM profile is starting to be raised as a priority for 'high value' and 'advanced' manufacturing, and a number of regional AM focused funding initiatives and project based research have been identified across Europe, or is on the horizon, future coordination of such activities is required. For instance, the development of AM since the onset of European Framework projects would seem somewhat divided into sub-areas of mostly fragmented research topics and not necessarily coordinated in a centralised format to enable maximised exploitation of AM technologies across the board. Also the 'realisation' of its true potential, especially on an economic and social scale is not necessarily visible. The latter requires the act of looking beyond just the technological means of AM.

“There are a lot of programmes at the moment within the EU focusing on ‘tweaking’ AM processes to try and make them incrementally a little bit better. We need a big scale concerted effort, maybe central” (Reeves, 2013)

“We believe that the currently available AM platforms, for instance Laser Sintering platforms, have not seen great steps in the recent past but small incremental improvements and what we would need is a more significant increased improvement in the value proposition in AM to push technology adoption ahead in these areas” (Baumers, 2013)

Global Reactions

Countries outside the EU are also raising their awareness and interest in AM, with research priorities being raised for AM in the US, Australia and emerging markets such as China for example.

US Obama Initiative

The US is following the lead of Europe and is currently exerting efforts in the field of AM. The US Administration has recently launched a partnership, the National Additive Manufacturing Innovation Institute (NAMII), with the aim of mainstreaming AM within industry in order to boost the manufacturing economy within the US. The institute intends to bring together a network of universities, colleges, industry partners and non-profit organisations with the ultimate aim of building a national presence and network for AM. They are reporting an almost $40 million match to the $30 million federal investment.

The US sees AM impacting positively on the US economy in the areas of defence, energy, aerospace, medical and commercial. They see its unique abilities as a good alternative to conventional manufacturing for rapidly making complex parts in smaller volumes and the promise for creating parts in-situ. The assumed longer-term impact is in the highly customised manufacturing area, where the technique can be more cost-effective than traditional methods (United States Department of Commerce - Commerce.Gov , Submitted on August 15, 2012 - 2:00pm).

Australia

In March 2011, an AM technology roadmap (Wohlers Associates, Inc., 2011) for Australia was created that was commissioned by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), an Australian Government Initiative. The roadmap was aimed at metals, with a particular importance on titanium. The roadmap included the identification of the main drivers, market opportunities and future technology needs for AM technologies.

In terms of their future, a large research initiative has been launched and key priorities will focus on metal powder AM production processes, AM systems for 'home' design and manufacture, economic studies demonstrating AM value, new materials for AM processing, and surface finish and post-processing techniques (Martin, February 28, 2013).

Company Acquisitions

The strong growth in the AM industry has resulted in a number of high profile company acquisitions being brought about in a bid to enhance their AM activities. For example, in 2012 GE Aviation acquired Morris Technologies, and its sister company Rapid Quality Manufacturing, who specialise in Additive Manufacture. GE acquired this company to expand its engineering and manufacturing capabilities in a bid to meet its production rates for an increasing jet engine line (General Electric (GE), November 20, 2012).

In January 2012, 3D systems, acquired Z Corporation (a provider of personal and professional 3D printers, 3D scanners, proprietary print materials and printer services) and Vidar Systems Corporation (medical film scanners that digitize film for radiology, oncology, mammography and dental applications). In May 2012, 3D systems also acquired Bespoke Innovations, an industrial design company developing products to be created on demand, and in July 2012 acquired Viztu Technologies, a provider of 3D scanning and imaging solutions (Kirkely, September 26, 2012).

Standards and Certification

New and disruptive manufacturing approaches need to institute standards to enable adoption and exploitation. The AM industry is starting to respond to this need on a global, national and regional level and a number of committee forums have been created.

ASTM F42 Committee

The ASTM F42 committee on AM Technologies was formed in 2009 and has a worldwide membership involving individuals from academia, industry (including machine manufacturers and end-users) and government. F42 has already published a list of standard terminology, as part of an ambitious standardisation programme.

ISO Technical Committee (TC 261)

In an attempt to standardise AM on a global scale, ISO has also created a technical committee (TC 261) to begin discussions on standardisation in the field of AM concerning their processes, terms and definitions, process chains (Hard- and Software), test procedures, quality parameters and supply agreements. The work being conducted to agree standards is very much in the early phases but shows a commitment to promoting the technology across various industrial sectors.

SASAM

The Support Action for Standardisation in AM (SASAM) was instigated in September 2012 to drive growth of AM by integrating and coordinating standardisation activities for Europe through creating and supporting a standardisation organisation in the field of AM (Scapolo, et al., December 2012).

BSI Committee

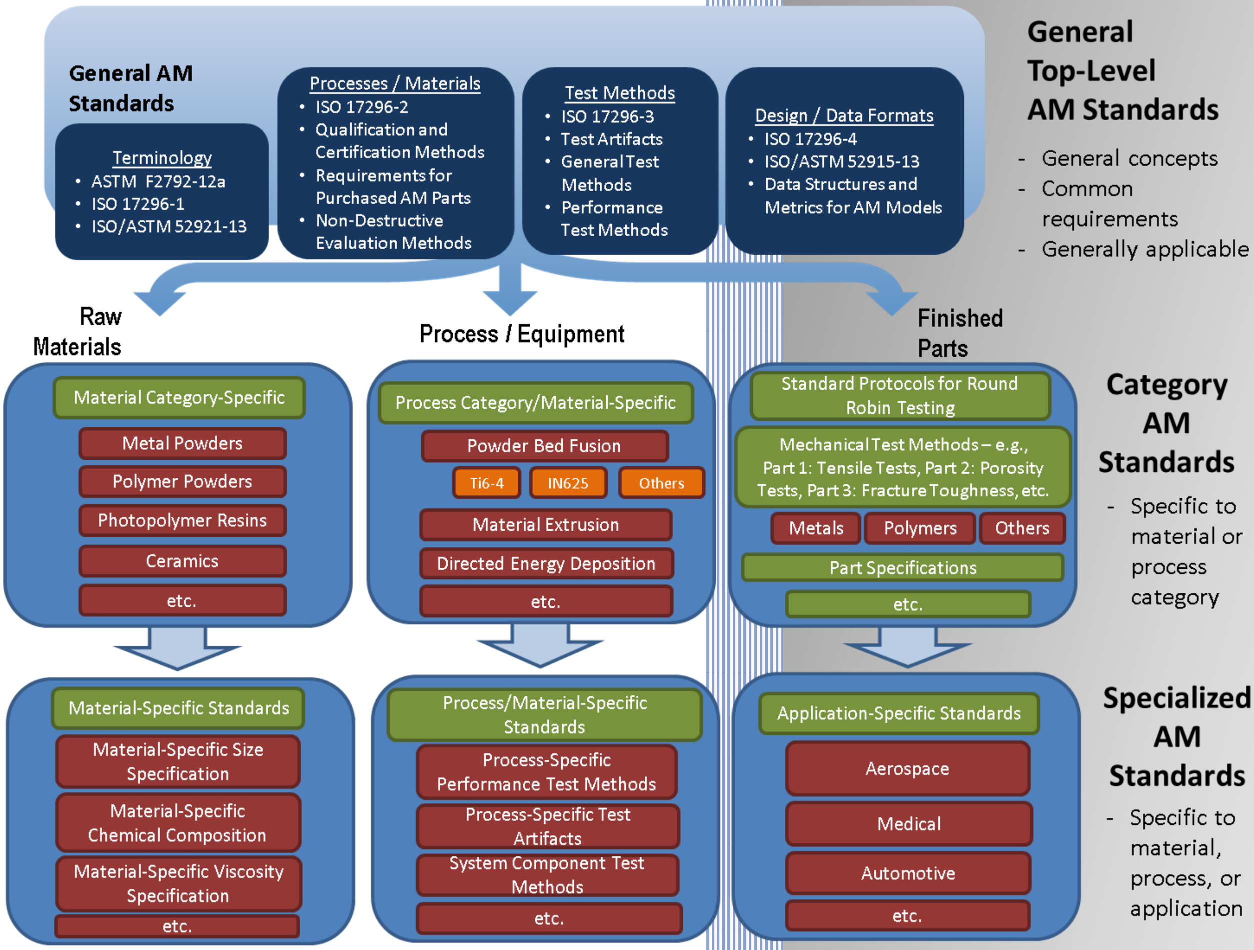
In the UK, BSI (British Standards Institution) is developing standards for AM under the AMT/8 committee. There are currently seven standards in development covering terminology; methods, processes and materials; and test methods (The British Standards Institution, 2013).

CEN/STAIR-AM:

The platform from CEN/STAIR (European Committee for standardization - STAndardization, Innovation and Research group) complements the SASAM project. Additive manufacturing is a new R&D-intensive sector with a potential wide market application and this platform brings together R&D experts and standardization experts in order to build the standardization process at the European level (by working with ISO).

UNM 920:
In France, AFNOR/UNM is developing standards for AM under the UNM 920 committee “Additive manufacturing”. Three standards have been published on terminology, technical specifications for powders, specifications and acceptance test for parts made by additive manufacturing.

The following structure for AM standards has been agreed by ISO and ASTM in July 2013 (Diagram courtesy of UNM Bureau de Normalisation par délégation d'AFNOR):



DEFINITION

AM refers to a group of technologies that build physical objects directly from 3D Computer-Aided Design (CAD) data. AM adds liquid, sheet, wire or powdered materials, layer-by-layer, to form component parts with little or no subsequent processing requirements. This approach provides a number of advantages, including un-rivalled geometric freedom of design, near 100% material utilisation, and short lead times.

The ASTM has defined 'Additive Manufacturing' as a (ASTM International, 2012):

"process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining."

Since the onset of layer based processing for creating 3D components, a number of terms have evolved and as such various terminology derivations have arisen. In more recent times, this has resulted in some misunderstanding or misuse of the terminology contributing to a 'weakness' in its advancement. The innovative nature of the technology and lack of available standardisation have also contributed to this.

'Rapid Prototyping' seems to be the earliest describer and tends to be deemed 'layer based processing for creating 3D components in its infancy'. However, considerable progress in the field has taken the technology far beyond that of 'prototyping'. 3D printing, a term brought about in the 90s, has been widely used since and has become a widespread term for creating layered 3D components, more generally known for low-cost 3D home printing and some of the larger commercial 3D printing systems. The term 'Additive Manufacturing' was later introduced and seems to have taken the position for describing the technology overall, and more specifically for industrial applications and professional high end equipment and applications. Figure 1 lists a number of terms for AM.

Figure 1: Schematic outlining the alternative terms in the field of AM

Following discussions with a number of experts within this field and making reference to the Draft Foresight Standard (Scapolo, et al., December 2012) and the ASTM F42 Committee (ASTM International, 2012), '3D-printing' and 'Additive Manufacturing', will be used for this documents.

Managing Expectations

Below a number of myths that surround AM are rejected. An associated comment aimed at being a more realistic interpretation has been added:

- There is not unlimited design freedom, BUT there is great design freedom
- It is not ‘rapid’, BUT it is very agile and adaptable
- AM does not yet have 100% material usage, BUT it is getting close
- AM will not be suitable for all applications, BUT it is currently especially good for small batches of complex and customised/complex parts

These points are very general comments, but there has to be some realism to the expectations from AM, and the promotion of AM should not over-promise its capabilities. The industry needs to be careful to not 'oversell' itself and therefore, when addressing future needs, expectations need to be managed appropriately.

Process Terminology

AM processes can be categorised by the type of material used, the deposition technique or by the way the material is fused or solidified. Process terminology is being defined by the ASTM F42 committee. The processes types have been categorised into seven areas as follows:

Process	Definition	Material	Example Usage
Vat Photopolymerisation	Liquid photopolymer in a vat is selectively cured by light-activated polymerisation.	**Photopolymer and Ceramic**	• Mostly prototypes for fit, form and functionality. • Consumer toys and electronics. • Some guides, jigs and fixtures.
Material Jetting	Droplets of build material are selectively deposited.	**Photopolymer and Wax**	• Casting and non-structural metallic parts. • Some metal end-use parts.
Binder Jetting	Liquid bonding agent is selectively deposited to join powder materials.	**Metal, Polymer and Ceramic**	• Marketing prototypes with colour. • Tooling. • Automotive covers/trim kits/dashboards. • Consumer electronics.
Material Extrusion	Material is selectively dispensed through a nozzle or orifice.	**Polymer**	• 3D objects with low structural property requirements. • Tooling. • Light and modular structures (hollow spheres).
Powder Bed Fusion	Thermal energy selectively fuses regions of a powder bed.	**Metal, polymer, ceramic**	• 3D objects of polymers or metals. • Tooling. • Secondary/tertiary structures. • Orthopaedic and dental implants. • Mechanical joints/sub-components/ducting.
Sheet Lamination	A process in which sheets of material are bonded to form an object.	**Hybrids, metallic and ceramic**	• Large parts. • Tooling. • Non-structural parts.
Directed Energy Deposition	A process in which focused thermal energy is used to fuse materials by melting as the material is being deposited.	**Metal: powder and wire**	• Re-work of articles. • 3D objects. • End-use parts with low structural property requirements.

Table: Classification of AM processes adapted from the ASTM (ASTM International, 2012), the Technology Innovation Needs Analysis by the AM SIG (Materials KTN, 2012) and the Additive 101: A General Purpose User's Guide (Shinbara, Posted 8 January 2013) The information here that has been adapted is purely for information purposes. It is not intended to replace any official definitions and is not a completely exhaustive list.

Technology Readiness Levels

To gauge the current manufacturing maturity of AM it is useful to measure AM applications against the Technology Readiness Level (TRL) scale. Following initial development from NASA other organisations, companies and industry have widely accepted the TRL scale as a way of measuring the maturity of the application of technology. An adopted schematic of this is presented as Figure 2. For the purpose of this comparison, TRL and MCRL are considered equivalent.

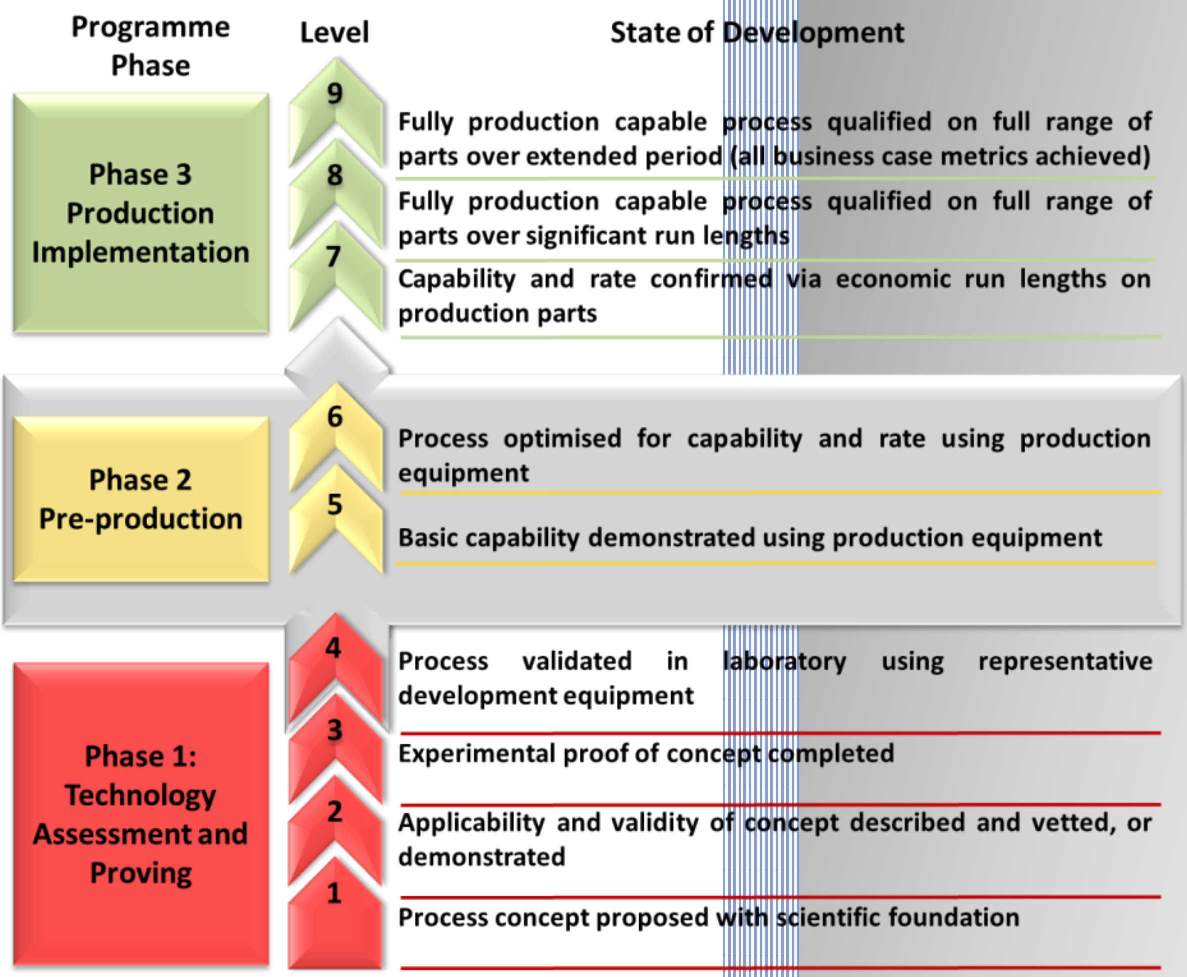


Figure 2: Manufacturing Capability Readiness Level (MCRL), part of the Technology Readiness Level (TRL) approach (Adapted from Rolls-Royce Plc CRL level guide).

Considering the AM development and exploitation that is in the public domain, it is evident that individual applications are at all points on this scale. For example, the creation of single crystal turbine blades could be viewed as being at TRL 1, and the manufacture of simple plastic components at TRL 9. Overall however, the following observations can be made:

- Many elements of AM are in the 'productionisation' phase; applications have been developed and are awaiting exploitation. This would equate to approximately TRL 4.

- The AM of plastics is, in general, at a higher TRL scale (TRL 7-9) than that of metals (TRL 3-7). However, the additive manufacture of plastics with good engineering properties is generally lower (TRL 4-5). Other materials are generally lower than this (TRL 1-3), for example ceramics.

- The majority of components being considered for aerospace manufacture are around the TRL 4-6 level, with specific 'secondary' issues facing the final deployment.

- Repair and servicing for the Aerospace industry is a high value-added activity and is readily applied in production (i.e. TRL9). However, the ability to reverse engineer a section to determine repair requirements and subsequently apply them is currently at TRL 5-6.

The above conclusions are by no means absolute, there are many applications at all levels. However, for AM to progress, the large amount of applications that are at or approaching TRL 4 need to be exploited for commercial gain.

TRL 4-6, known as the 'valley of death' (highlighted in Figure 2), are traditionally the key areas to developing a process for production, and are therefore, the main areas where applications fail. It is comparatively easy and cost effective to prove that an application can be done in a laboratory. It requires a lot more development and investment to achieve process capability and stability in full production.

A written publication (www.ukparliment.co.uk, Prepared 20th April 2012) from Rolls-Royce reported that the 'valley of death' generally reflects the difficulty of getting a new technology through TRLs 4 to 7. It reports that companies and countries that do not offer funding mechanisms to support these TRL levels can be at a severe competitive disadvantage. It also reports 'a manufacturing process requires development so that the final products can be manufactured economically, in volume and with consistent quality'. For this to happen TRL and MCRL must be managed together so as to not waste investment or delay entry to the market, or launch products of low quality or high cost.

MARKETS

The AM industry is expected to have continued strong growth in the medium to long term. It was estimated at $1.7 billion for 2011, by 2015 the sale of AM products and services is predicted to reach $3.7 billion. In terms of AM machines, the plastics market is leading with currently around 30,000 machines in the field. There is also growth in metallic AM, with the metal parts market having over 500 machines sold to date (Wohlers, 2012) and despite the global recession, it is expected that metal AM machines will see double digit percentage increased growth in sales over the next five years.

Survey results from Wohlers 2012 also indicate that AM technology is being used by companies more for direct part production (20%) and then for patterns for prototype tooling (12.2%) and metal casting (12.1%).

In terms of industry specifics, AM has flourished considerably in the last few years in particular areas. However, there are two distinct markets which are slowly developing for products made by AM; one is the industrial/production market, which includes medical, (orthopaedic implants) dental, aerospace, automotive and power generation. The other is the consumer market including home accessories, fashion and entertainment. Within these sectors, AM will be key in product development.

Following a survey of AM system manufacturers and service providers, Figure 3 shows the breakdown of the percentage of industrial sectors using AM (Wohlers, 2012).

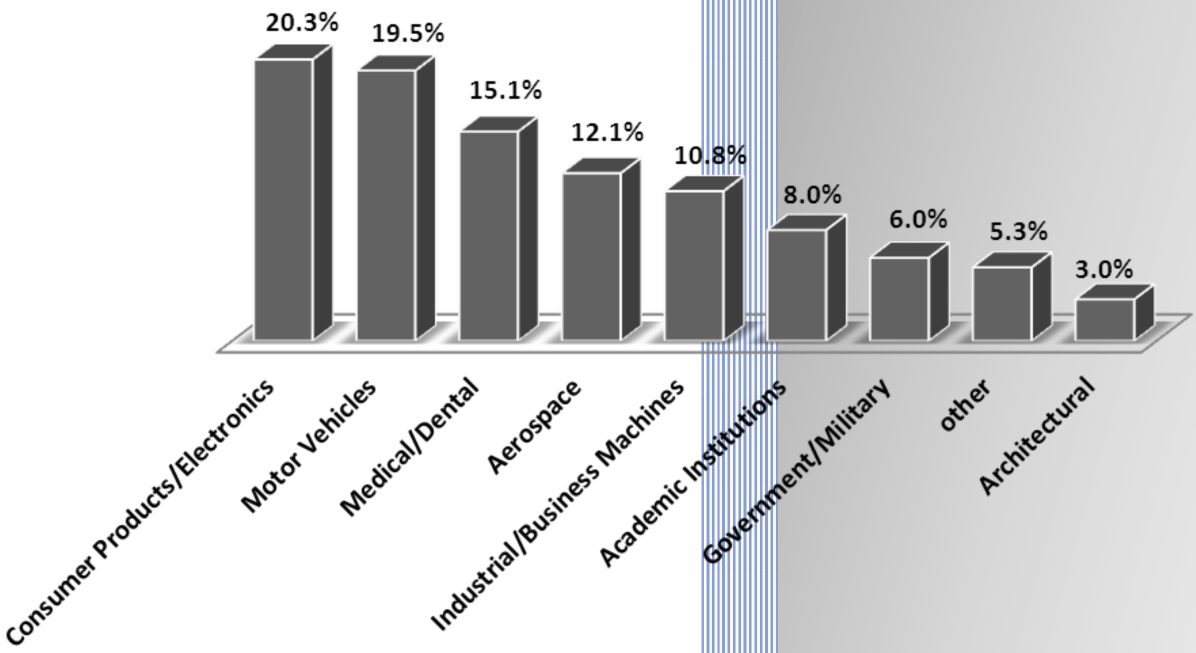


Figure 3: Breakdown of the percentage of industrial sectors using AM (Adapted from Wohlers, 2012).

Figure 4 shows the size of the AM market for specific materials with a simplified prediction for significant future growth.

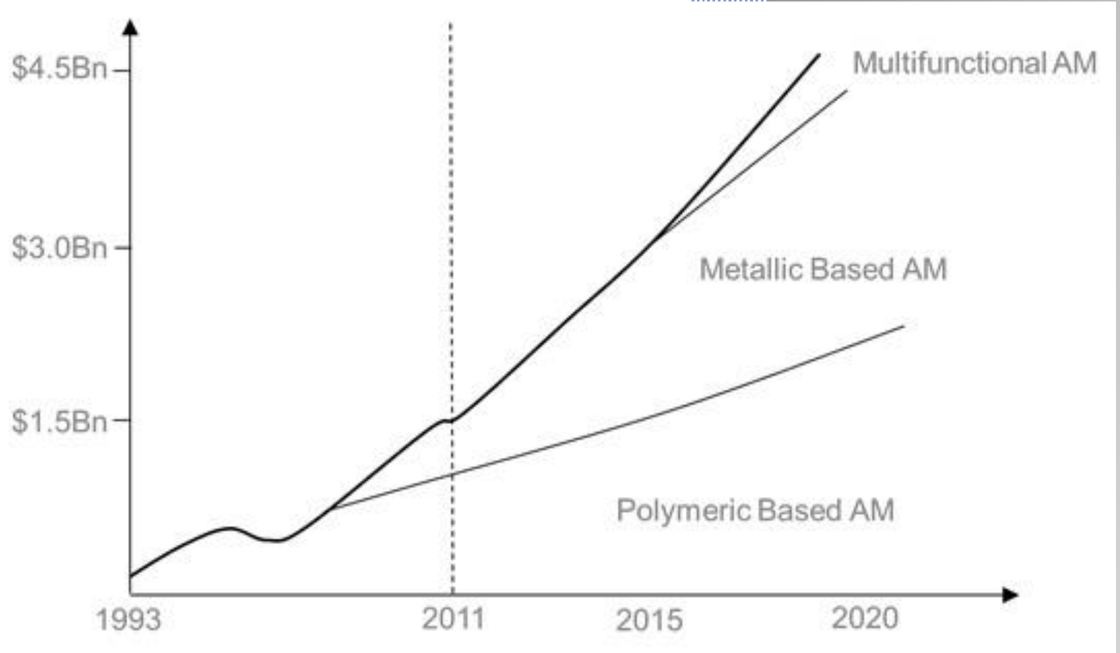


Figure 4 Simplified actual and predicted AM market including material usage (Courtesy of TWI)

Industry/Production Markets

Medical

Medical and dental has established itself as a strong sector for AM, including metals, and has been the third largest sector using the technology over the past ten years (Wohlers, 2012). Within the UK, the Medical Sector is a large sponsor of AM. SIG reported contributions of £3 million to lever AM research activities of £11.5million (Materials KTN, 2012).

AM is impacting medicine in more than one important way, AM techniques have been applied within the medical and dental arena for the creation of assistive, surgical and prosthetic devices, surgical implants, and scaffolds for tissue engineering. It was recognised quite early that AM could bring great improvements to the fields of prosthetics and implantation. For instance, applications are gaining wide interest due to the nature of the process allowing complex parts to be created specifically for the patient directly from a 3D CAD model which has been created from a patient's CT or MRI scan. Accurate patient specific implants produced using the 3D scan data can reduce the removal of healthy bone, eliminate the need for bone grafting, promote effective planning of implantation/surgery and shorten the time of anaesthesia. There are also predications that the customisation enabled by AM will result in increased implant-life.

Aerospace

AM growth in the Aerospace sector has increased from 9.9% to 12.1% in 2011 and 2012 respectively; this follows increasing investment (Wohlers, 2012). The UK SIG (Materials KTN, 2012)[4] reported that the UK Aerospace industry have invested £13 million in AM research.

The aerospace market is quite varied in the use of AM, with many examples of niche components being made and supplied using various forms of AM (in both polymers and metals). One of the key drivers in manufacturing of high value aerospace components is improving the buy-to-fly ratio of metallic components; which are typically 5-20. Figure 5 highlights why AM is such an attractive potential alternative manufacturing route, due primarily to its high material use efficiency and ability to process aerospace grade titanium and nickel alloys.

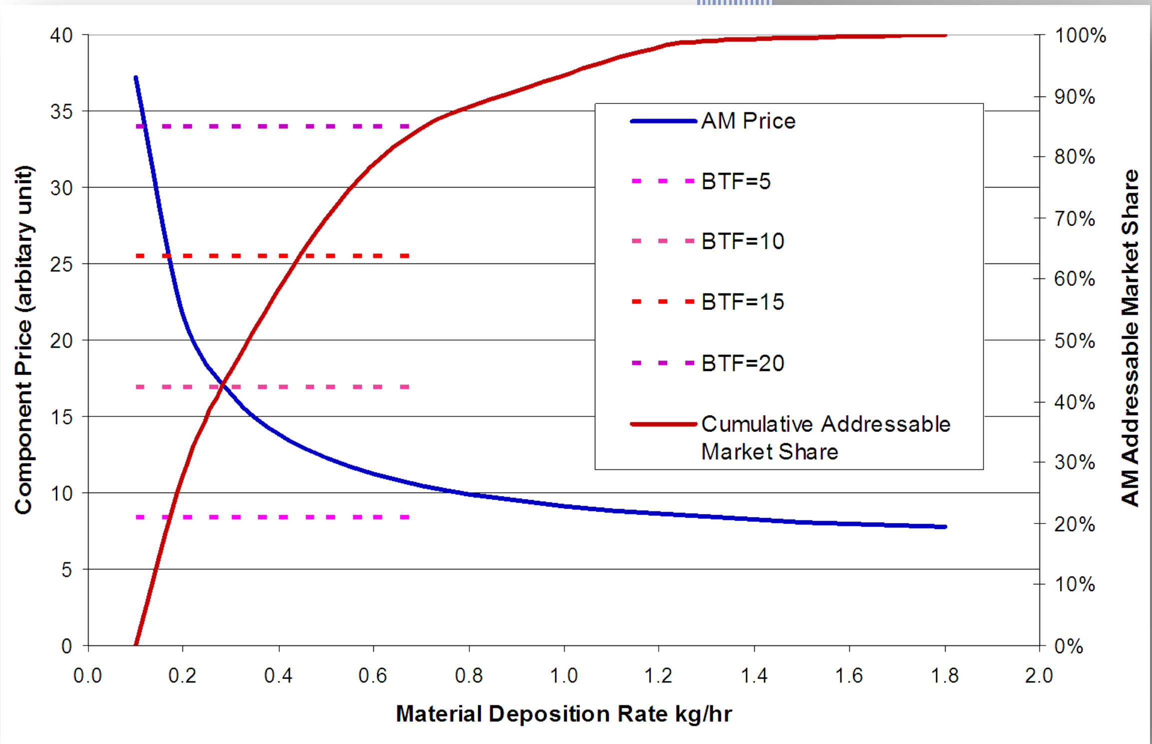


Figure 5: Analysis of component price vs. material (metal) deposition rate in AM, with 'break even' point compared to traditional machining manufacture at typical aerospace buy-to-fly ratios (Tomlin & Meyer, 2011).

In the aerospace sector, AM is seen as an enabling technology for light-weighting or topology optimisation, because of its capability to create complex structures. This can have the additional benefits of improving performance and reducing waste, because of the ability to recycle the feedstock. AM has also been used for testing of complex or difficult to implement designs, including extensive tests in 'full engine' rigs.

Automotive

Automotive has established itself as a strong sector for AM, and is the second largest sector as reported by Wohlers (Wohlers, 2012). In the UK, the automotive sector is a large supporter of AM research funding, contributing £3.5million to lever AM research activities of £6.5million (Materials KTN, 2012).

More and more car manufacturers are using the benefits of AM in the production of concept cars. The process opens a new world of design freedom and allows concept cars to be built faster than with more traditional methods. 3D models are used for everything from concept creation to production planning, allowing design engineers to speed up and improve the development process. The automotive industry has historically used AM as an integral tool in the design process. The fast-paced design cycles in the automotive industry require a rapid prototyping solution that can produce almost any geometry with a variety of material properties, quickly and cost effectively.

Examples of recent concept cars consisting of AM technologies include: Mazda's Kiyora, Pininfarina's Sintesi, Citroën's Hypnos and GT and Renault's Ondelios, see Figure 6.

Figure 6: (left) A Laser sintered dashboard by Materialise for the Renault Ondelios concept car (above) (Courtesy of Renault) (Source: http://www.renault.co.uk/about/innovations/ondelios.aspx)

Consumer Market

Consumer Products/Electronics

Survey results from Wohlers 2012, showed consumer products/electronics as the leading sector and reported that it had been for the last seven years (Wohlers, 2012).

In the UK, when combining the creative industries, consumer products and fashion/home categories as one generic sector, SIG UK reported that this sector accessed some £2.5million of industry contribution to lever around £7.5million support for the sector (Materials KTN, 2012).

One of the principle uses of AM parts in the consumer goods industry is to produce prototypes and models. Although making prototypes remains the main use of additive fabrication, the technology has increasingly spread into 'rapid manufacturing' - also termed "direct digital manufacturing" (DDM) by the Society of Manufacturing Engineers - as well as into rapid tooling. One industry projection for the future would involve the use of a single machine for the design, prototype, and creation of a finished part.

Within the consumer market there is a large array of products also being manufactured by AM including toys, games, home furnishings, fashion items, sports equipment etc. Artists, jewellers and fashion designers are using AM in a range of ways including to produce one off bespoke pieces.

Fashion

In March 2013, a 3D Printing Company, Shapeways, revealed a 3D printed gown in Nylon designed by Michael Schmidt and Francis Bitonti. The gown was modelled by Dita Von Teese (see Figure 7) which had been built from a number of 3D printed components that were designed to specifically fit Von Teeese's frame. This shows the distinct freedom of design possibilities to 3D print complex and highly personalised items. Shapeways reported that as 3D printing matures, and is able to process finer and more flexible materials, the fashion world will see more from 3D printing (Shapeways, 5 March 2013)

Figure 7: 3D printed gown modeled by Dita von Teese (Design: Michael Schmidt and Francis Bitonti. Image courtesy of Albert Sanchez. http://albertsanchez.com Source: http://francisbitonti.com/#Dita-s-Gown)

Another example of 3D printing, is the recently released Nike Vapor Laser Talon. This is a 3D printed shoe and as a result they weight a mere 5.6 oz. This new design was created using Selective Laser Sintering and provides the ability for increased acceleration but also helps the athlete to maintain their speed for a longer duration.

Nike had to change its method of manufacturing and changed to 3D printing because of its capabilities to create the cleat plate within a fraction of the traditional manufacturing lead time and at a fraction of the weight. Also, the traditional manufacturing method was not able to accept mass production of the required shape of the shoe (Nike, Inc., 2013)[52].

Another example is the “Head Over Heels” woman’s shoe (Figure 8) which was a collaboration project between designer Sjors Bergmans and TNO within the European research project, CEC Shoe.

Figure 8: Additive shoe (courtesy of TNO).

Electronics

AM of electronic devices and components has seen growing interest. Similarities between AM and Direct Write technologies can also be made, particularly for the deposition of conductive materials onto conformal surfaces.

Inkjet printing methods are emerging as the front runner for electronic applications using AM technologies (Gausemeier, et al., 2011). Inkjet technology can be used to print passive circuit components such as resistors, capacitors and inductors, as well as diodes, Organic Light Emitting Diodes (OLEDs) and circuit interconnections (Sridhar, et al., 2010).

Figure 9: Inkjet printed OLED display by Cambridge Display Technology.

CHALLENGES & OPPORTUNITIES

Additive Manufacturing is disruptive in nature and has the potential scope to transform new ideas and methodologies outside of 'conventional' industry norms.

> *"As a comparatively young technology, AM already today raises high expectations. Since AM is NOT just another technology to replace conventional ones but requires a new thinking in entire business models, progress is needed in various elements of such a chain. Ignoring that and pushing AM too hard into traditional rules at this early stage may inflict damage on the technology and also ruin market reputation"*
>
> *(Lenz, 2013)*

The UK AM Special Interest Group (SIG (Materials KTN, 2012)) reported that a very limited number of AM technologies have similar applications. However, they also reported that research suggests that all industries and their sectors have a keen interest in developing AM, especially where 'design freedom', 'customisation' or 'cloned part manufacture for short production runs' is desirable.

The differentiation between AM technologies, for example between low-cost 'home-printing' and industrial/production, is a factor that needs to be taken into consideration when deciphering the needs of industry regarding AM. However, there is a lot of common ground that should be factored into any future strategy development.

For these reasons the following sections have been structured in a manner which attempts to highlight the key sectors where AM has a large influence or is 'most' active. A general section is included in order that a focal point providing common 'overarching' themes where most key challenges and opportunities within and across all industries and technologies can be addressed.

To highlight this methodology, the key PESTLE drivers, along with examples of products or processes within these drivers that are relevant to AM are detailed. Emphasis is then drawn down to highlighting some of the key technology challenges/opportunities, which, if addressed, have the potential to overcome the barriers to AM adoption and contribute to tackling a number of the PESTLE drivers. This is by no means an exhaustive list and some of the areas for development may not be explicitly detailed in all the appropriate areas/industries. Figure 10 provides a schematic of the process methodology used for mapping the AM themes.

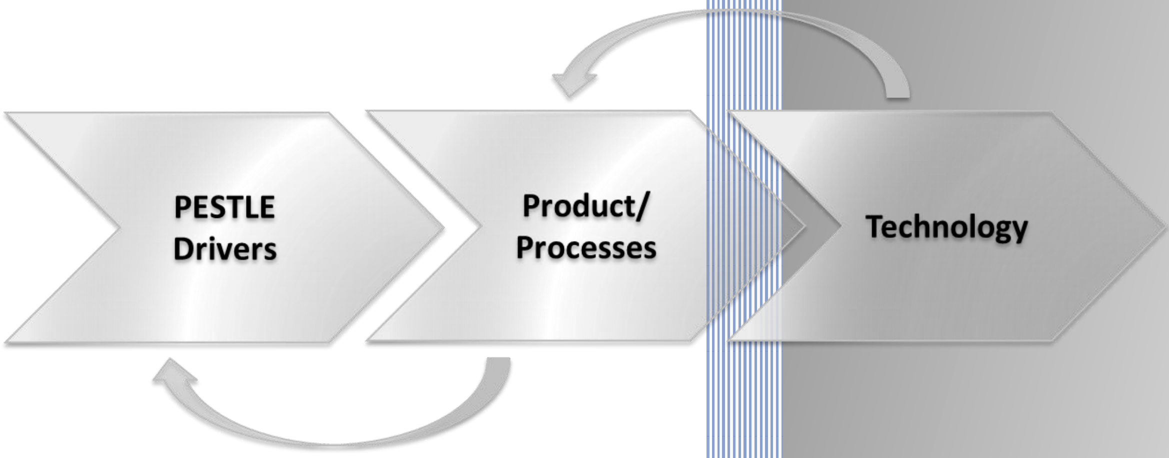


Figure 10: Schematic of the process methodology used for mapping the AM themes.

Along with the experts that contributed to this document, the information in the following sections has also been derived from a number of sources within the public domain including the Technology Innovation Needs Analysis Conducted by the AM Special Interest Group for the Technology Strategy Board, (Materials KTN, 2012), the Draft Foresight Study (Scapolo, et al., December 2012), the AM - Status and Opportunities (Scott, et al., March 2012), Thinking ahead the future of Additive Manufacturing – Innovation Roadmapping of Required Advancements (Gausemeier, et al., 2013), Thinking ahead the future of Additive Manufacturing – Promising Industries (Gausemeier, et al., 2012) and Emerging Global trends in AM (Shipp, et al., 2012)

"AM today is understood by many parties (media, press, public and politics) as a low end 3D printing technology for smart "home printing" application rather than as a future production technology. Although both ways will find their way in the future, trends, barriers and research priorities differ fundamentally. Topics like standardisation, intellectual property rights and liability must be considered completely different depending on what technology and applications you look at" (Lenz, 2013)

Medical & Dental

Drivers

- Personalisation
- Mass customisation
- Increased efficiency of supply chain
- Regulatory requirements
- Ageing population
- Obesity and associated health risks
- Miniaturisation
- Safety
- Quicker response times
- Device life extension
- Entrepreneurship
- Bio-compatibility

Products Relevant to AM

Mass customisation is key in the medical industry. As with EOS dental copings and bridges solutions, where individualised parts can already be economically built, other applications will follow. " (Lenz, 2013)

AM is impacting the medical and dental sector in several important ways. AM techniques have been applied within the medical and dental arena for the creation of:

- Dental Implants: bridges and crowns
- Surgical guides
- Orthopaedic implants
- Hearing aids
- Scaffolds for tissue engineering
- Other assistive, surgical and prosthetic devices

The Direct Metal Laser Sintering (DMLS) process has been used for some time to produce crowns and bridges and has managed to become a reputable form of manufacturing for these products within the dental industry. EOS is reporting that their EOSINT M270 systems are able to work within an accuracy of +/- 20 microns and produce over 400 units within 24 hours at low cost. In terms of productivity, this relates to 3 minutes per unit. Not only this, the labour input is significantly reduced resulting in further decreased costs and the high accuracy and quality parts produced maintain the high standards required by the market (EOS - e-Manufacturing Solution, 2013)[60].

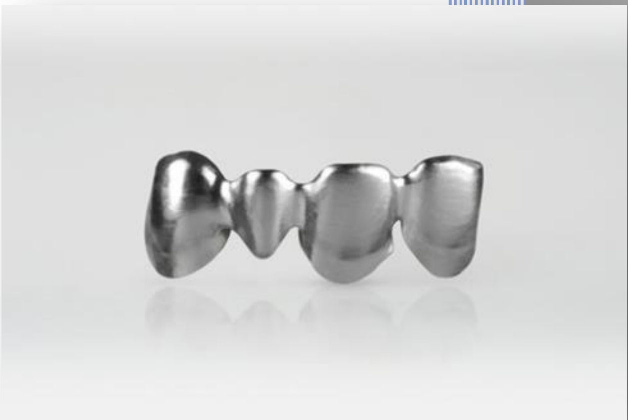


Figure 11: EOS Cobalt Chrome SP2 polished bridge produced by the EOSINT M270 Image courtesy of EOS GmbH (EOS - e-Manufacturing Solution, 2013) *(source: http://www.eos.info/press/press_material)*

In medical applications it is imperative to decrease product development time while simultaneously providing functional performance. It was recognised quite early that AM could bring great improvements in this area, and a wide range of applications are now gaining momentum. Accurate patient specific implants produced using the 3D scan data can reduce the removal of healthy bone, eliminate the need for bone grafting, promote effective planning of implantation/surgery and shorten the time of anesthesia. There is also a part-life benefit.

Figure 12: Example of a customized Cranio-Maxillofacial implant for a severe head injury by EBM® Electron Beam Melting process. Image courtesy of (Arcam AB, 2013). *(Source: http://ir.arcam.se/om-arcam/pressmaterial/.)*

Challenges/Opportunities

- Modelling methods for customised implants and medical devices.
- Development of modelling tools to ensure functionality of parts and increase the understanding of how it will perform after surgery.
- Further improvements in eliminating steps in the process chain.
- Development of viable processes for fabrication of ‘smart scaffolds’ and for construction of 3D biological and tissue models.
- Creation of bio-AM including modelling, analysis and simulation of cell responses and cell tissue growth behaviour.
- Automation assessment of design and process planning tools.
- Development of lower cost materials in order to reduce the costs.
- Validation of mechanical and thermal properties of existing materials and AM technologies including part characterisation.
- Development and characterisation of new materials for AM e.g. magnesium, copper, bio-degradable polymers, etc.)
- Changing the way designers think to increase understanding of design freedom.
- AM quality and process stability for medical/dental applications.
- Development of optical and mechanical properties for the dental market e.g. colouring.

Aerospace

Drivers

- Reducing buy-to-fly ratio
- Light weighting
- Increased efficiency of supply chain
- Energy usage (improved fuel efficiency)
- Life cycle cost
- Design freedom ‘new’ or ‘optimised’
- Life extension
- Performance of materials
- Utilisation of materials
- Cost
- Simplified assembly process
- Production efficiency
- Validation in full scale engine tests
- Reduction of time to design and test an aero engine

Products Relevant to AM

“AM perfectly matches the challenges of lightweighting in the aerospace industry. The industry already invests heavily to qualify AM for production purposes. Even though this will still take a lot of time and effort, the impact will be huge”. (Lenz, 2013)

Example applications by AM:

- A French company, Microturbo, are collaborating with the Advanced Manufacturing CRC (AMCRC) to develop methods for producing aerospace microengine components with reduced process chains, material waste, and design cycles for parts (Martin, Posted on February 10, 2012).
- GE Aviation plan to produce metal parts by AM, namely a fuel injector and a leading edge for fan blades in its gas turbine engines (Wohlers, 12 April 2012)
- Morris Technology has produced a rotor which has been laser-sintered from Nickel Alloy IN718 and a fuel injection nozzle for gas turbine applications.

Although AM is predominantly being used to produce aerospace prototypes (Figure 13) for engine testing and other fit and functional uses, it is expected with further research and development that the technology will be increasingly used for production of actual flying parts.

Figure 13: Stator ring Material: NickelAlloy IN718.Image courtesy of Morris Technologies / General Electric Aviation (source:http://www.eos.info/press/press_material)

EADS has been researching into the area AM for some time and is developing various aerospace applications using the technology. AM offers design flexibility and reduced weight, material waste and hence reduced costs. For example, EADS has been testing wing brackets and hinges for engine covers to evaluate the technical and commercial feasibility of producing parts by AM. The results showed that considerable weight savings can be achieved, see Figure 14 (Tomlin & Meyer, 2011).

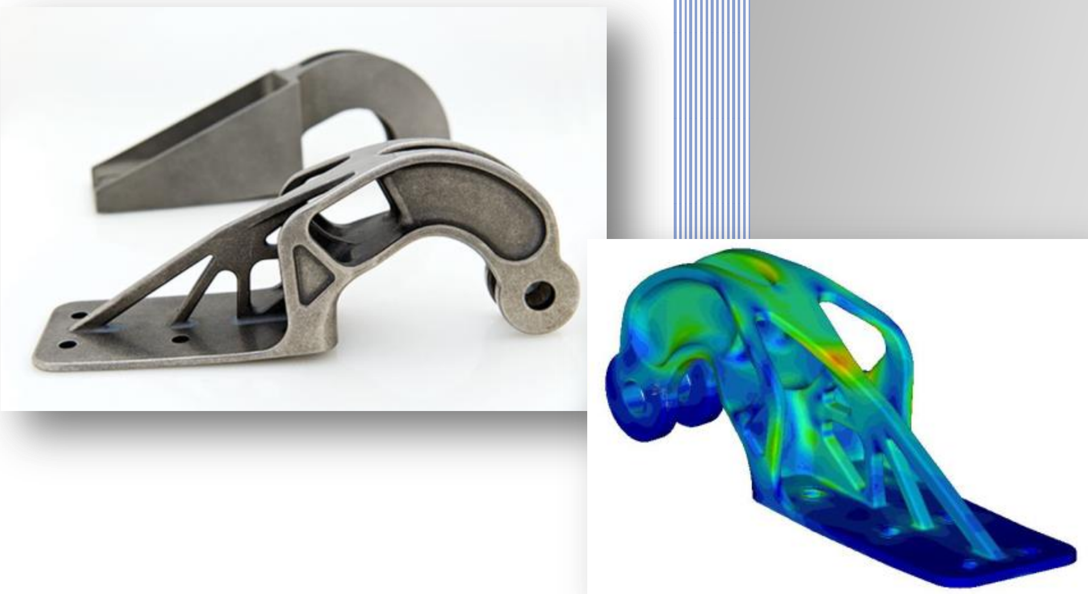


Figure 14: Titanium bracket with optimised topology made by using DMLS technology Bracket images courtesy of EADS Innovation Works (source: http://www.eos.info/press/customer_case_studies/eads). Optimised topology image courtesy of "Added Value by Laser Assisted Additive Manufacturing" – AVLAM. AVLAM was a collaboration project managed by TWI Ltd partly funded by the TSB under Reference: AB183A.)

Another area of importance for AM, is repair applications. For example a Laser Metal Deposition (LMD) process repair procedure was developed for Rolls-Royce's turbine seal segments. Rolls-Royce endorsed the installation of a LMD production facility to repair their Trent 500 segments allowing them to save significant costs over the lifecycle of their Trent turbines.

Repair and servicing of aircraft is a very high value-added activity that is highly profitable. The ability of AM to enable more advanced repair operations through selective re-application of advanced alloy materials (e.g IN718, etc) has wide interest. However, the ability to reverse engineer a section to determine repair requirements and subsequently apply them is currently at TRL 5-6. Further support from the CAD industry and non-destructive testing technologies (for purposes of validation and certification) is also necessary to enhance the repair, scanning, design and analysis capabilities.

These applications show that AM is gaining considerable importance within the Aerospace Industry and one where the key drivers are particularly influencing its direction, such as the need for light-weighting, reduced life cycle costs and the demand for increased performance of materials and individuality of internal aircraft features. AM is also being developed for cabin applications e.g. a titanium, internal structure bracket for a 777 aircraft (Loughborough University , 2013). However, further developments within AM technologies will be required to fully quantify the possibilities for the Aerospace industry and a significant effort is needed to quantify these parts for service.

Technology Challenges/Opportunities

- Further development of complex shaped structures (e.g. lattice structures).
- Development of new process modelling and support techniques.
- Processing of light-weight materials (e.g. as titanium alloys).
- Processing of new multi-materials.
- Quality and consistency of powder production.
- Processing of materials with improved functionality.
- Processing of difficult to machine and weld materials (e.g. Nickel and Titanium super-alloys).
- Development of improved buy-to-fly ratio of metallic components.
- Implementation of AM industry standards for aerospace applications.
- Simplified assembly of complex parts through optimised AM design.
- Producing larger airframe structures through AM technologies.
- More advanced repair operations through selective re-application of advanced alloy materials (e.g. IN718).
- Development of improved fatigue properties and the effect of surface finish.
- Further development of process control and reproducibility of nozzle-based AM techniques, which are currently around TRL 5-6.
- Further development of current repair requirements and its application by AM techniques.
- Supplementary developments from the CAD industry and NDT technologies for the purposes of validation and certification.
- Improvements on process control and on dynamic (fatigue) materials properties.
- Development of good modelling tools for materials processing.
- Development of surface quality and finishing of complex structure.
- Closed loop control.

Automotive

Drivers

- Light weighting
- Increased efficiency of supply chain
- Increased quality
- Reliability
- Reproducibility
- Recyclability
- Reducing vehicles carbon emissions
- Design freedom
- Cost effectiveness

Products Relevant to AM

> *"Individuality or mass customisation are important trends driving change so increased product diversity is important for the future and for meeting individual customer requirements. AM has great potential for freedom of design that can cope with these challenges". (Wall, 2013)*

Additive Manufacturing in the automotive industry is largely limited to the prototyping of components as a design and engineering validation tool. It has also seen uses to make small parts and sub-assemblies for both visual analysis and quality control. However, to date, there are a limited number of examples of this technology being used to produce final production parts in vehicles (Richardson & Haylock, 2012)[49] except for specialist applications such as emergency vehicles.

Example AM applications:

- BMW are using a Stratasys 3D Production System to build hand-tools for assembly and testing of automobiles (Stratasys Ltd. , 2013).
- Joe Gibbs racing (JGR) are creating complex carbon monoxide filter housings for their cars using FDM from Stratasys. FDM processes the polycarbonate (PC) material, which has a higher temperature rating than the previous material used (Stratasys Ltd, 2013).

- The MINI John Cooper rally car used FDM for design assessment and testing and is now using AM for production parts that include the door mirror base, tyre temperature sensor housing, driver display pod and many others (see Figure 15).

Figure 15 Prodrive's MINI John Cooper Works WRC race with 15 FDM parts. Image courtesy of Prodrive (Doe, November 2012).

AM Challenges/Opportunities

- Development of larger certified build chambers.
- Development of common design rules.
- Increased process reliability.
- Reproducibility of parts.
- Hybrid manufacturing.
- Development of higher production rates and cheaper systems.
- Development of improved process stability.
- Development of standardisation and certification.
- Cost per unit part.
- Production quantities are needed.

Consumer/Electronics

Drivers

- Tailored products/customisation
- Increased efficiency of supply chain
- Increased functionality
- Enhanced materials
- Sustainability of raw materials
- Higher demand for colourful items
- Demand for innovative products

Products Relevant to AM

"The market niche (home and school) is foreseen as a huge market when small systems at affordable price for individuals can bring useful and usable parts to play, to eat, to repair, to substitute….." (Anguera, 2013)

Consumer

Example consumer applications by AM:

- MGX Materialise are producing customised lighting (Figure 16) using AM techniques such as Selective Laser Sintering (MGX by Materialise, www.mgxbymaterialise.com, 2013).

- Freedom of Creation are using AM for producing exclusive design objects, furnishings, lighting and accessories (Freedom of Creation, Powdered by 3D Systems, 2013).

- Shapeways are using AM for producing customised and limited edition products, such as one off bespoke fashion items e.g. (Figure 7) the 3D printed gown modelled by Dita Von Teese (Shapeways, 5 March 2013).

- The sports industry is taking advantage of AM technology for producing sports equipment e.g. (Figure 8) Nike used 3D printing to create a cleat plate a training shoe (Nike, Inc., 2013).

These are just a small selection of the final use products produced by AM techniques. An increasing amount of companies want to take advantage of the vast and unique possibilities AM technology has to offer and it will see further usage when more usable and enhanced materials are developed. Currently parts may be functional but the aesthetics and material properties need improvements therefore the development of higher quality parts is required.

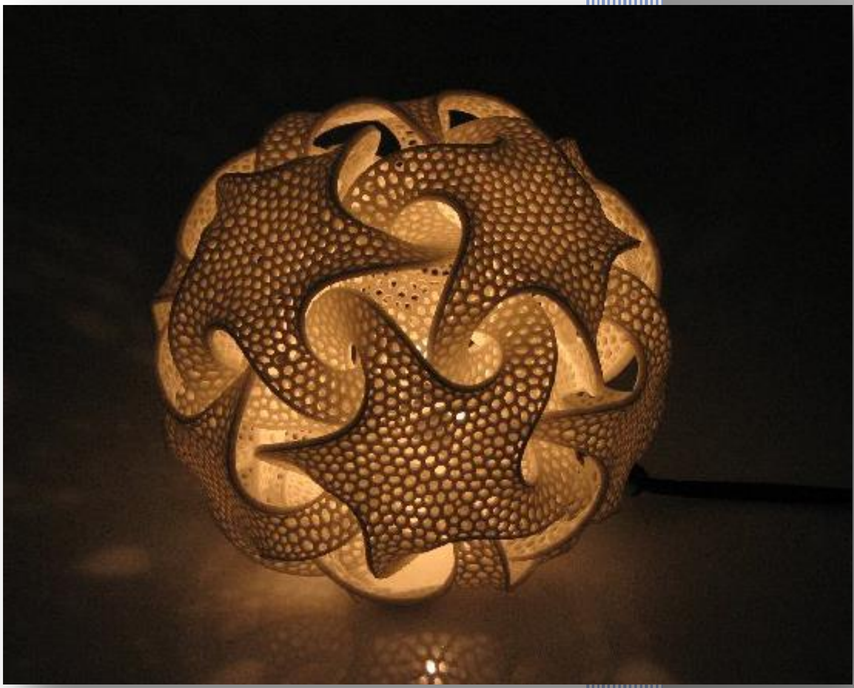
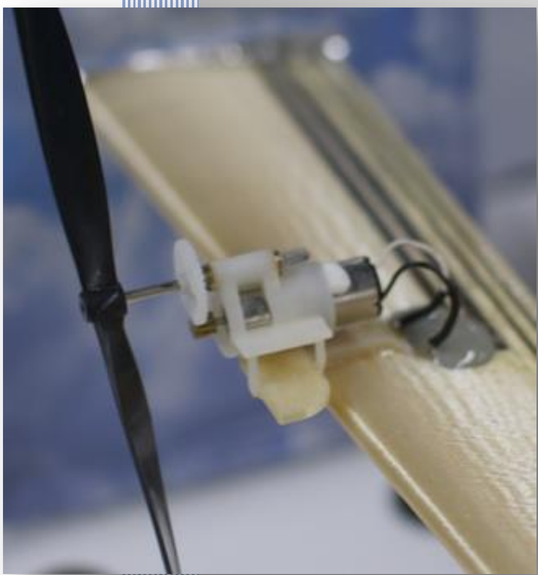


Figure 16: QUIN.MGX lamp. Designed by Bathsheba Grossman
Courtesy of Materialise (MGX by Materialise, www.mgxbymaterialise.com, 2013).

Electronics

Stratasys and Optomec Inc combined efforts of AM and printed electronics with the result of producing a fully printed hybrid structure (Figure 17), a 'smart wing' model structure for an unmanned aerial vehicle (UAV). Stratasys manufactured the wing structures using FDM and then Optomec used its Aerosol Jet process to print the electronic circuits and active devices directly onto the wing structures (Watson, March 2012).

Figure 17 : UAV 'Smart wings' with printed circuits powering a propeller and LED Image courtesy of Stratasys, Optomec and Aurora Flight Sciences.



DMRC reports (Gausemeier, et al., 2012) the electronics industry as a 'promising' industry for AM and details a numbers of applications especially the production of manufacturing and tools equipment. There is also increasing demand for the production of embedded electronics.

Manufacturing Challenges/Opportunities

- Materials development e.g. metallic and high tech ceramics.
- Development of multi-materials e.g. coated coloured material or parts.
- Education for high technology AM for generating understanding and awareness.
- Parts may be functional but the aesthetics need improvement therefore the development of higher quality parts is required e.g. improved surface finish and better material properties.
- Material systems need to meet the requirement of consumer goods.

GENERAL

Drivers

- Design freedom
- Light weighting
- Changing customer/consumer demands
- Ageing population
- Individualism
- Complex part creation
- Multi-functionality
- Optimised structures
- Reduced costs
- National priorities
- Simplified supply chains
- New manufacturing capabilities
- Increasing competitiveness
- Improved productivity
- Skills and knowledge
- Mass customisation
- Localised manufacturing
- Material and energy utilisation
- Environmental Impacts
- Higher performance systems

Challenges/Opportunities

Experts in the field of AM raised a number of similar technical challenges and research priorities, particularly for process repeatability and stability, development of materials, increased quality and productivity, requirement for reduced post-processing activities, supply chain management and system integration. In terms of the more non-technical areas for development standards/certification, reduction of costs, data sharing, value creation and liability were the most stated. Although a number of these are not new to the industry they are still very valid and it is felt that there is still considerable research required in a number of 'common' themes for the AM industry in order that the barriers to further exploitation are overcome.

Process Stability

Process stability for AM needs to aspire to 'right every time' production. Key areas for improvement include:

- Material processability, quality and performance
- 'Right first time' processing
- Larger parts and process scale-up
- Process tolerances
- Temperature management
- Improved surface finish
- Geometrical stability
- Improved process control/monitoring
- Energy consumption
- Laser development
- Multi-material manufacturing
- Reduction of residual stresses
- Software deployment

Productivity

AM processes are in almost all cases not capable of supporting high-volume production due to productivity limitations. AM is a slow process because of the layered nature of the techniques. Future developments are required in:

- Increasing build speed through new approaches to scanning or sources of energy to increase productivity.
- Decreasing the time to create each layer, the overall time between layers, and start up and shut down time.
- Developing methodologies to ensure consistent materials supply and measurement techniques for AM products.

"The big issue is economics and largely the economic problem/priority is making these machines faster. Even if you bring them down in price with the current throughput achieved from the machines, you would end up having a factory full of machines in order to get anything near production volumes, and that in itself then has a huge overhead associated with it. What we need is machines that don't just consolidate 40g of Titanium in an hour, we need something that consolidates 40kg of Titanium in an hour, but does it at a similar quality and capability of today" (Reeves, 2013)

Materials

Material processability is key to the performance of a part. Currently, each end user goes through an extensive validation exercise often, including both static and fatigue testing in the case of metallics, to confirm the material performance. Material, new or existing, properties and qualification are required for AM processing for existing and new material systems in order to increase the capabilities of AM technologies for industrial applications.

Further developments are required in the:

- Development of AM materials performance (static and fatigue) to be a similar demonstrable performance level of cast and wrought material.
- Development of materials' consistency and repeatability e.g. fixing process parameters.
- Interchange-ability of process parameters between different AM machines

New materials development suitable for AM processing:

- Analysis of properties of different materials and multi-materials using AM techniques, including their validation.
- Identification of new semi-crystalline and amorphous polymers suited to different AM mechanisms.
- Analysis and development of biomaterials, superconductors and new magnetic materials, high performance metal alloys, ultra-high temperature ceramic composites, metal-organic frameworks, new Nano-particulate and Nano-fibre materials.

Process and Product Quality

In-line process control and monitoring methods are limited for AM. These are particularly required for production of safety related components, for example in Automotive or Aerospace applications. Therefore, there is a need for further development in the areas of:

- In-process monitoring and control methodologies including techniques for reducing post-processing activities.
- Hybrid manufacturing combining AM processes to meet geometric and surface finish requirements including the locating of parts and subsequent adaptation of process control.
- In-situ sensors to provide non-destructive evaluation and allow for early detection of flaws/defects.

Improved surface finish is required, as a high quality surface finish can allow a part to be taken off the platform and used directly without any further finishing. Subsequent development of:

- Material characteristics and the mechanisms by which the material is processed.
- The development of smaller parts and features achieved through handling of powder particle sizes less than 10 microns.
- Development of the power-beam (laser or electron beam) and material interaction(s) and associated changes required in in-process control.

AM Data

Limited access to performance data for AM components, materials and processing parameters:

- Development of shared databases providing a catalogue of materials performance information for particular applications, materials or AM processes
- Development of an 'online' portal for materials information sharing

The processes and product data for AM are comparatively immature resulting in a number of applications being observed at a low TRL:

- Database development for showcasing applications with details of AM being utilised in different sectors, and highlighting the TRL including the known barriers to adoption. Maintain focus on sector specific AM research (Materials KTN, 2012)

AM Industry Definition

As the AM industry is growing, there are also a number of diverse themes developing. These themes require different approaches in terms of their future development technologies:

- Technology and research requirements need to be categorised as to fit the diverse range of AM technologies, especially for standardisation, liability and intellectual property.
- Supply chains for AM technologies are underdeveloped and can often be fragmented. Therefore the development of an industry sector network focussing on developing AM supply chains of common areas and capabilities are required.

Training and Education

There is a lack of education of practitioners in AM capabilities. This is further affected through cultural differences, vested interests and potentially, lack of imagination. In Order to overcome these barriers a number of educational activities are recommended:

- Development of a series of training modules for specific AM processes, materials and application sectors.
- University and technical college courses, education materials, and curricula at basic undergraduate and post-graduate levels
- Training programs for industry practitioners, perhaps with certification by professional societies or organisations (e.g., ASME).
- Outreach programmes for the non-technical population, i.e. programs for management or other non-technical business personnel on logistics, lean manufacturing, new business models, etc. Educating the general public would enhance the interest in AM applications and generate some societal “pull” for these technologies.
- Raising awareness of AM technology across all sectors through events based on industry case studies, knowledge transfer and supply chain assistance.
- AM 'design-for-manufacture' seminars on how to make use of the technology.
- More education books dedicated to increasing the knowledge of AM technologies, materials and their applications.

Standards and Certification

There is a general recognition that a lack of standards has been limiting the uptake of AM in key industrial sectors e.g. aerospace and medical/dental. The availability of standards will help to increase adoption of the technologies and open up extensive research and development opportunities.

Professional markets are often demanding and require certification which makes adoption of new technologies very difficult. There is a need to:

- Develop processes to enable certification of AM. For example the development of advanced in-process inspection and quality control techniques to ensure standards are being maintained.
- Develop methodologies for preventing or correcting defects.
- Engaging industry further in the ASTM F42, BSI and ISO working groups.

Liability

There are a number of implications brought about concerning liability, especially for amateur or unknowledgeable designers, part manufacturers or distributors. Should a part fail, who is responsible? This is an area of increasing concern for the AM industry especially where flexibility, individuality and self-designing can introduce unfamiliar territory. New business models for the supply of parts made using AM technology and the associated business risks need to be developed.

Intellectual Property

There is concern that AM technology is controlled by a few organisations through the protection of relevant Intellectual Property thus restricting competition and the identification of new applications. This is not only slowing innovation, but is keeping system costs high. There is also a powerful influence being seen by those controlling distribution channels, for example where machine manufacturers specify the purchase of specific raw materials in order to maintain warranty or ensure health and safety.

AM could have a major impact on intellectual property, as objects described in a digital file could be much easier to copy, distribute and pirate. The very same scenario that occurs with the music and movie industry could happen with the development of new non-commercial models and an increasing tension between hampering innovation and encouraging piracy (Scapolo, et al., December 2012)

"In other digitally driven economies or digitally driven industries or supply chains there is an enormous amount of value in the data and I think we have largely overlooked the value of data….. We need to consider the value proposition of digital data, what is it you are going to make, how valuable is it, how do you make it, how do you sell it, how do you control it? There is a lot of research needed in this area (Phil Reeves, 2013)

Environment

Future manufacturing will be measured increasingly on its environmental footprint. AM has distinct advantages over more conventional processing such as material utilisation/recycling validation, light-weighting of components for transport applications and enables localised manufacturing with reduced 'cost of logistics' across the supply-chain further strategies are required.

The near 100% material utilisation involved in AM is a distinct advantage to wasteful processes such as machining. 'Buy to use' ratios can be 20:1 by weight, or higher. This is clearly not sustainable in the long term from an environmental or economic stand point. More effort is also required in the validation and standardisation of the batch to batch recycling of materials in AM, especially with regards to polymeric materials.

AM techniques have room for improvement regarding their overall approach. For example, the heat sources used, such as lasers, need to be made more electrically efficient. The processes are too slow and therefore need to be more productive to reduce resource usage. As with most processes, in-process losses can be improved.

AM techniques are 'clean' in that they do not consume water, tooling, chemicals and are near 100% material efficient. True sustainability is achieved through not consuming natural resources. AM can reduce the use of material and assist in the reuse and recycling through improved design. More work needs to be done however, in the recycling of material using AM processes after the part has finished its natural usage life. This could involve melting of used parts, the monitoring and control of material chemistry, and the atomisation of this material to create feedstock for AM systems.

Costs

In production, for new technologies to be adopted clear and significant cost-performance benefits need to be established and justification of investment and risk associated with their implementation. There are a number of obvious areas where cost reduction will have the largest effect on AM:

- Increased processing speed/productivity
- Fast turnaround and addressing material/part/component handling
- Reduction in equipment and material costs
- Improved material utilisation
- A reduction in scrap/improved repeatability

Equipment and material costs are still high and future developments to drive down cost of equipment is required through:

- The identification of new supply chain opportunities and establishment of existing supply chains for potential products.
- Materials processing whereby new powder production sources or new/improved methodologies for supply chain integration are facilitated.

Advanced AM

The development of new/advanced AM machines is indicated to be highly important e.g. machines with multiple lasers. One challenge AM especially faces is multi-material processing, meaning the usage of several materials on the same machine (Gausemeier, et al., 2013)

Multi-material processing expands the potential of AM into areas of multi functionality and self-servicing. Considerable work has been done on the printing of human tissue, for example, in the biomedical field, including the printing of cells, bio-scaffolds and human organs, see Figure 18.

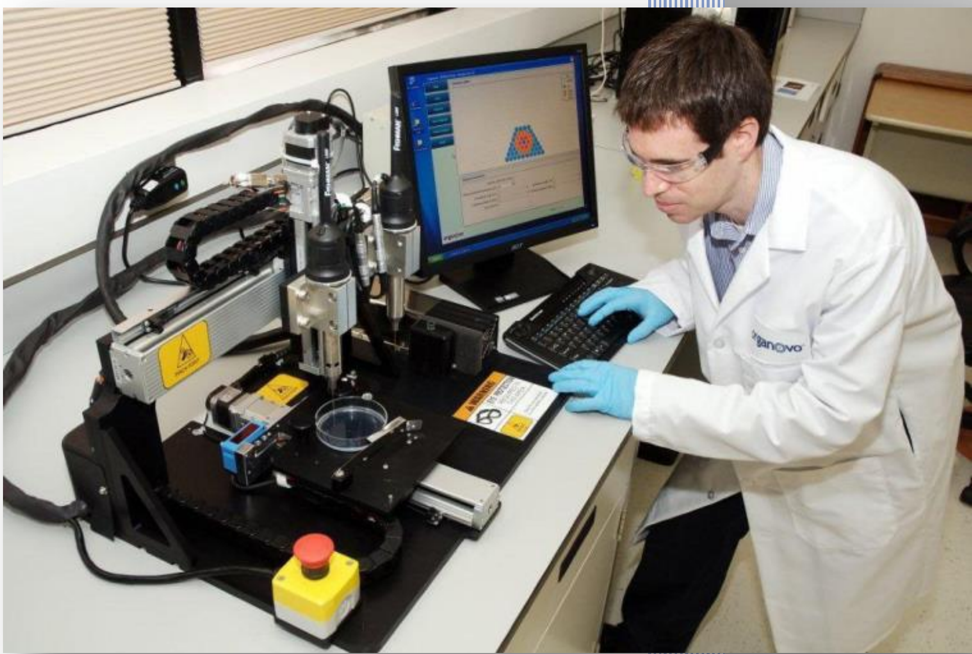


Figure 18 A commercially available 'human organ printing' AM machine. Courtesy Organovo Inc.

RECOMMENDATIONS

The following is a summary of the recommendations serviced from the SRA generation process:

TECHNICAL AM DEVELOPMENT	
Productivity	
Increase build-speed, possibly through new approaches to scanning or sources of energy.	Decrease the time to create each layer, the overall time between layers, and start-up and shut-down time.
Support higher volume production, possibly through enabling batch consistency and methodologies for consistent materials supply.	Develop methodologies for measurement of AM products.
The development of new/advanced AM machines e.g. machines with multiple lasers.	
Materials	
Develop AM materials performance, static and fatigue, to enable a similar or superior demonstrable performance level of cast and wrought material.	Develop materials' consistency and repeatability e.g. fixing process parameters.
Interchange-ability of process parameters between different AM machines.	Analyse material properties of different materials and multi-materials using AM techniques, including their validation.
Identification of new semi-crystalline and amorphous polymers suited to different AM mechanisms.	Analyse and develop of new materials for AM processing e.g. biomaterials, superconductors and new magnetic materials, high performance metal alloys, amorphous metals, ultra-high temperature ceramic composites, metal-organic frameworks, new nano-particulate and nano-fibre materials.
Tailored materials for AM.	Improve material utilisation.

Process and Stability	
Increase material processability, quality and performance.	Develop methodologies for 'Right first time' processing.
Increase control of process tolerances.	Develop tools for better temperature management during processing.
Improve surface finish of processed parts.	Improve geometrical stability.
Improve process control and monitoring.	Analyse energy consumption and development of methodologies for its reduction.
Further develop lasers with improved efficiency and control.	Develop multi-material manufacturing for AM technologies.
Reduce residual stresses.	Increase software utilisation.
Reduce scrap and improve repeatability.	Faster turnaround addressing material/part/component handling.
Materials processing whereby new powder production sources or new/improved methodologies for supply chain integration are facilitated.	Identification of new supply chain opportunities and establishment of existing supply chains for potential products.
Analyse stability of the AM process in order to make improvements to AM systems that will allow production components to be produced with required properties.	
Product Quality	
Develop in-process monitoring and control methodologies and systems including techniques for reducing the requirements for post-processing activities.	Investigate in-situ sensors to provide non-destructive evaluation and allow for early detection of flaws/defects.
Develop a 'streamlined' workflow for hybrid manufacturing, combining AM processes to meet geometric and surface finish requirements.	Develop design tools and methodologies to empower design engineers to take advantage of AM.
Develop material characteristics and the mechanism by which the material is processed to improve surface quality.	Increase the understanding of power-beam manipulation (laser or electron beam) and material interaction(s) and their associated changes particularly for smaller parts production for increased surface finish.
Develop databases to allow a catalogue of materials performance information for particular applications, materials and processes.	Develop an 'online' portal of materials information for comparison and sharing.

Economic, Social and Environmental AM Challenges	
Environment	
Improve the heat sources used in AM, for example more electrically efficient lasers.	Improve process productivity to reduce resource usage including in-process losses.
Validation and standardisation of the batch-to-batch recycling of materials, especially for polymeric materials.	Develop strategies for recycling material after the part has finished its natural usage life e.g. melting of used parts, the monitoring and control of material chemistry, and the atomisation of material to create feedstock for AM systems.
Standards and Certification	
Develop processes to increase certification of AM e.g. advanced in-process inspection and quality control techniques.	Further industry engagement in the ASTM F42, BSI and ISO working groups on standards development.
Develop methodologies for preventing or correcting product defects.	The following topics have been identified as a priority by ISO and ASTM: Qualification and certification methods, design guidelines, test methods for characteristics of raw materials, material recycling guidelines, standard protocols for round robin testing, standard test artefact, requirements for purchased AM parts, harmonization of existing ISO/ASTM terminology Standards, tests on finished parts.
Technology and research requirements need to be categorised as to fit the diverse range of AM technologies, especially for standardisation, liability and intellectual property.	An industry advisory group that focuses on AM supply chains and common areas of capabilities for Europe.
Develop new business models stating clear rules and guidelines on the effective supply of AM produced components to ensure product safety, but also accountability in the event of faulty or damaged parts/products.	
Training and Education	
Develop AM specific training modules encompassing design/ modelling, processes, materials and applications.	Non-technical outreach programmes for management, or other non-technical business personnel, on logistics, lean manufacturing and new business models.
University and technical college courses, education materials, and curricula at basic undergraduate and post-graduate levels.	Events based on specific industrial case studies, technology transfer support and supply chain assistance.
Training programs for industry practitioners certified by professional bodies.	More educational resources dedicated to increasing the knowledge of AM technologies, materials and their applications.

Other	
Global collaboration in the area of AM would be beneficial particularly between EU and USA.	Identification of applications and work with end-users to understand the business case for using AM over other manufacturing routes.
Mechanisms for taking a product into production e.g. taking proven concepts at TRL 4 and moving them to TRL 7 to 9.	Supply chain development, from material supply, reliable AM systems to post-processing.
Functionally graded structures in terms of design or material.	More consideration to the value proposition for AM e.g. digital data.
The creation of assemblies using AM.	Establishment of bio-tissue engineering using AM.

Medical & Dental	
Modelling methods for customised implants and medical devices.	Automation assessment of design and process planning tools.
Develop modelling tools to ensure functionality of parts and increase the understanding of how it will perform after surgery.	Develop cheaper materials in order to reduce the costs.
Further improvements in eliminating steps in the process chain.	Validation of mechanical and thermal properties of existing materials and AM technologies including part characterisation.
Develop viable processes for fabrication of 'smart scaffolds' and for construction of 3D biological and tissue models.	Develop and characterise new materials for AM e.g. magnesium, copper, bio-degradable polymers, etc.
Create Bio-AM including modelling, analysis and simulation of cell responses and cell tissue growth behaviour.	Changing the way designers think to enable increased understanding of 'freedom of design' that is free from manufacturing constraints

Automotive	
Develop larger certified build chambers.	Hybrid manufacturing.
Develop common design rules.	Develop higher production rates.
Increase process reliability.	Develop improved process stability.
Reproducibility of parts.	Develop standardisation and certification.

Consumer Products	
Materials development e.g. metallic and high tech ceramics.	Education needs for high technology AM for creating understanding and awareness.
Develop multi-materials e.g. coated coloured material or parts.	Develop higher quality parts for improved aesthetics.

Aerospace	
Develop complex shaped structures (e.g. lattice structures).	Produce larger airframe structures through AM technologies.
Develop new process modelling and support techniques.	More advanced repair operations through selective re-application of advanced alloy materials (e.g. IN718) and their validation.
Process light-weight materials (e.g. as titanium alloys)	Develop improved fatigue properties and the effect of surface finish.
Quality and consistency of powder production specific for AM.	Further develop process control and reproducibility of nozzle-based AM techniques, which are currently around TRL 5-6.
Process materials with improved functionality.	Supplementary development from the CAD industry and NDT technologies for the purposes of validation and certification.
Process difficult to machine and weld materials (e.g. Nickel and Titanium super-alloys).	Improve process control and dynamic (fatigue) materials properties.
Develop improved buy-to-fly ratio of metallic components.	Develop good modelling tools for materials processing
Implement AM industry standards for aerospace applications	Develop surface quality and finishing of complex structure.
Simplify assembly of complex parts through optimised AM design	

AM ROADMAP

In order to provide a more meaningful representation of the listed recommendations, a collective approach to the main topics has been established. To accommodate this, a methodology has been developed in which 'common' themes within, and across, the main topics of the recommendations (See Figure 19) have been grouped and prioritised, and subsequently depicted onto a roadmap, see Figures 20 and 21.

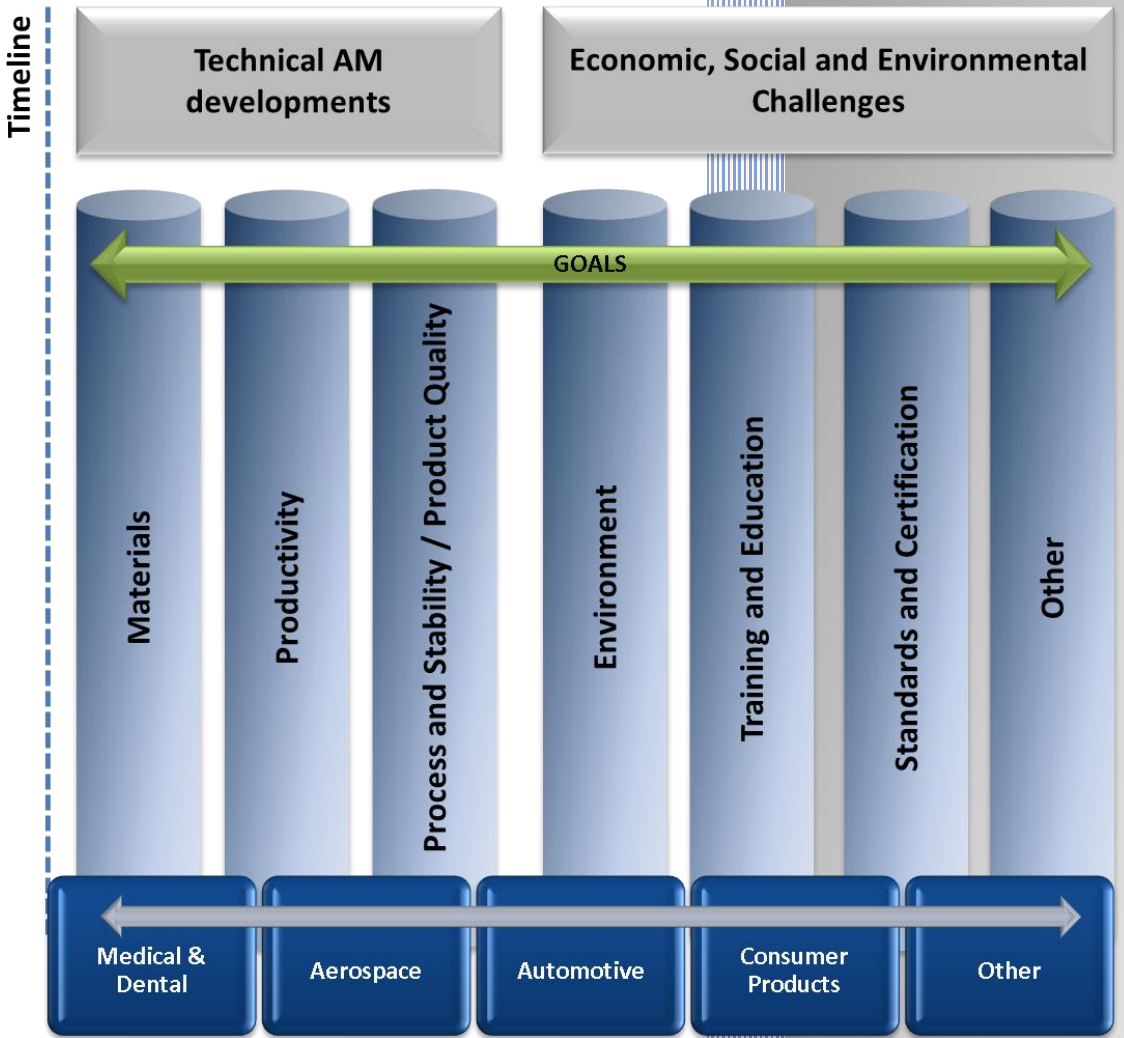


Figure 19: Common themes within and across the main topics of the recommendations.

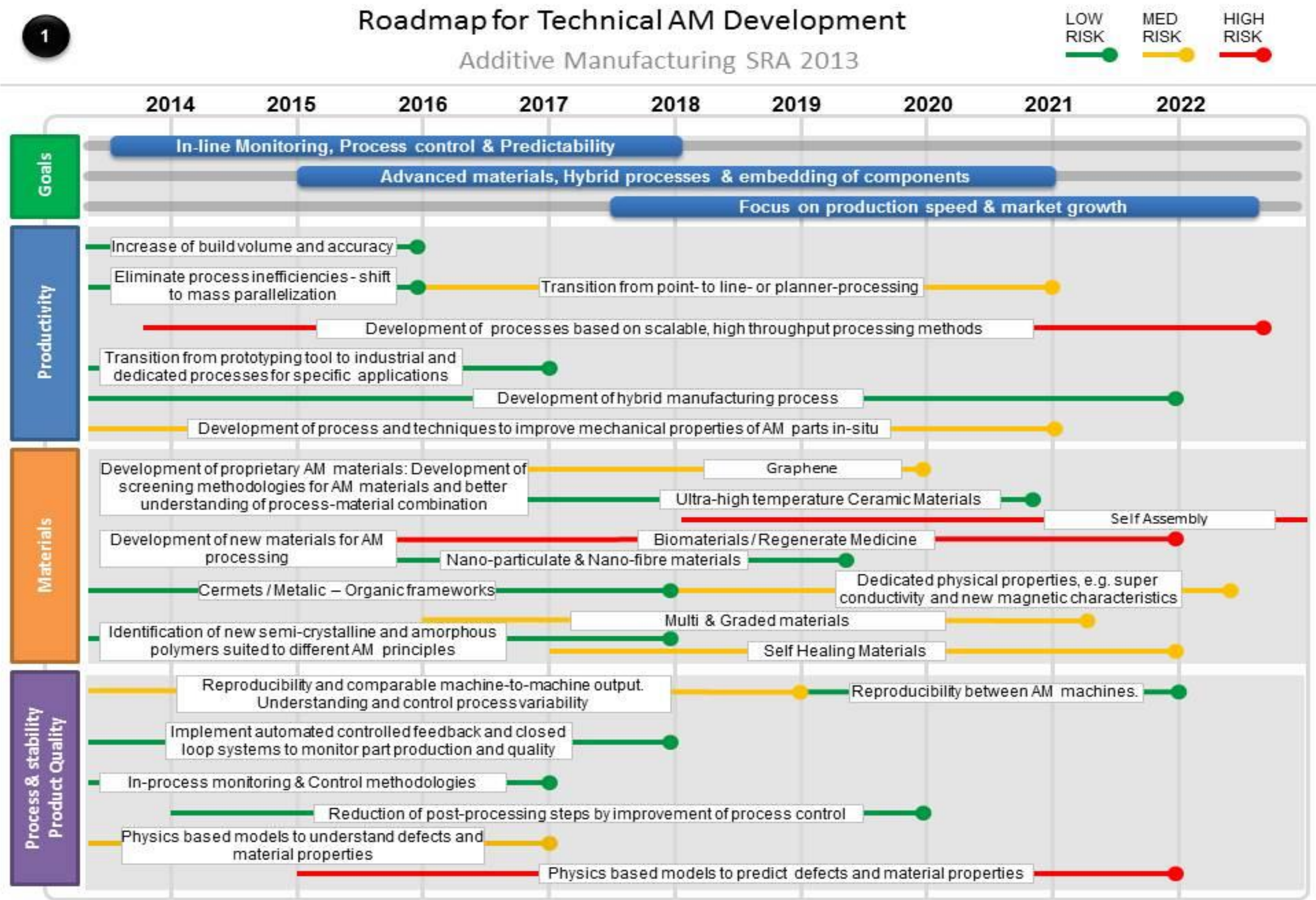


Figure 20: Timeline roadmap for Technical AM development.

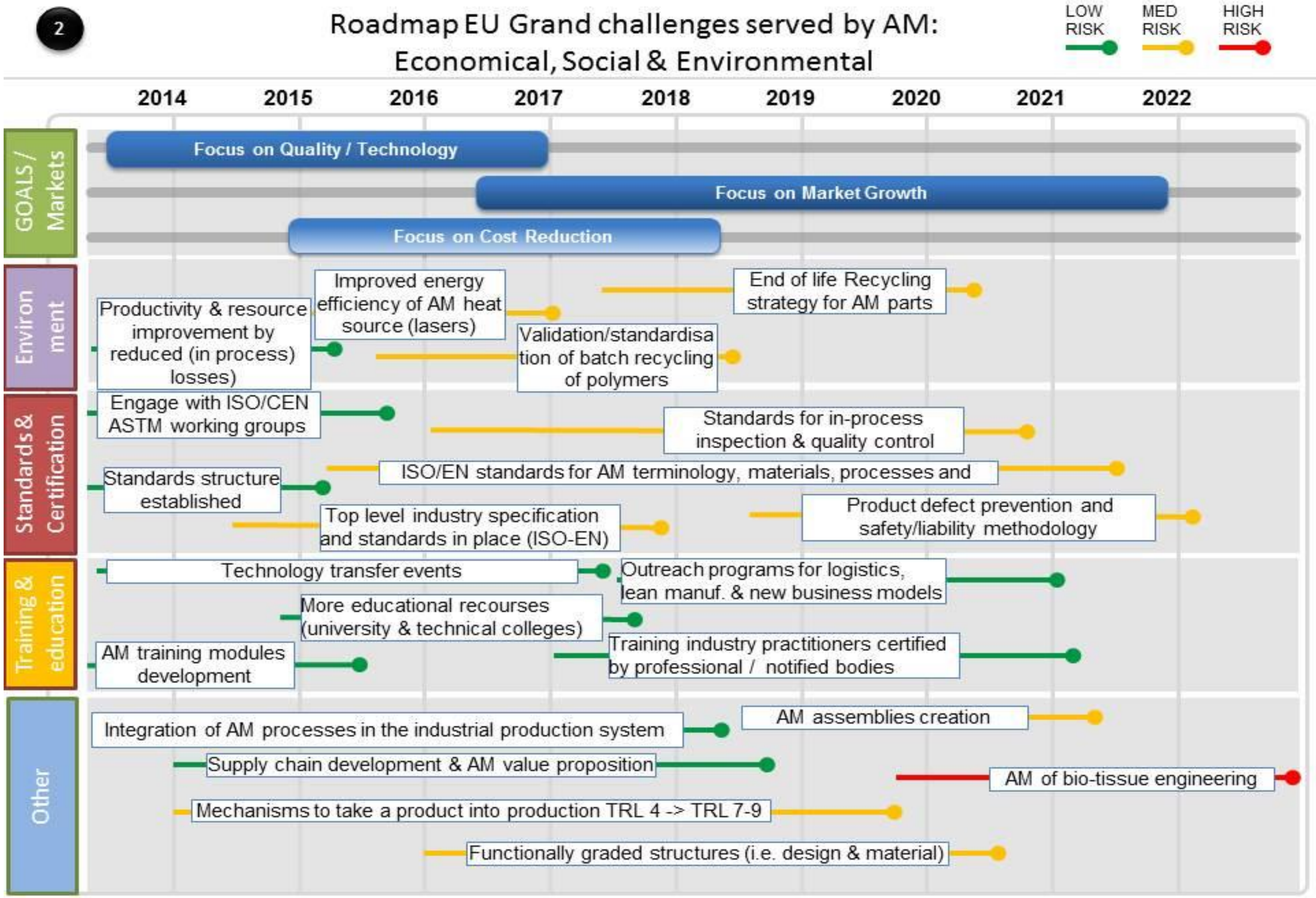


Figure 21: Timeline roadmap for EU grand challenges.

REFERENCES

Ad-hoc Industrial Advisory Group, 2010. *Factories of the Future PPP Strategic Multi-Annual Roadmap 2010-2013,* s.l.: European Commission.
Advisory Council for Aviation Research and Innovation in Europe (ACARE), September 2012. *Realising Europe's vision for aviation - Strategic Research & Innovation Agenda,* s.l.: s.n.
AM Platform, 2011. *Additive Manufacturing :Strategic Research Agenda 2011,* s.l.: s.n.
Anguera, M. G. i., 2013. *Additive Manufacturing Technology Sub-Platform - Topics and Questions.* s.l.:s.n.
Anon., 19 January 2011 . *A PESTLE Analysis for the Pharmaceutical Industry.* [Online]
Available at: http://www.strategic-planet.com/2011/01/a-pestle-analysis-for-the-pharmaceutical-industry/
[Accessed 23 March 2013].
Arcam AB, 2013. *Introducing the future in Implant Manufacturing.* [Online]
Available at: http://www.arcam.com/wp-content/uploads/Arcam-A1.pdf
[Accessed 19 April 2013].
ASTM International, 2012. *ASTM F2792 - 12a Standard Terminology for Additive Manufacturing Technologies,.* s.l.:ASTM International, West Conshohocken, PA.
ASTM International, 2012. *ASTM F2792-10. Standard Terminology for Additive Manufacturing Technologies.* s.l.:ASTM International, West Conshohocken, PA. www.astm.org..
Bessey, E. E., 15 May 2012. *Manufacturing Research & Innovation in Horizon 2020 - Baseline Document,* s.l.: Manufuture ETP.
CORDIS Search Service - European Union, 2013. *Simple Search.* [Online]
Available at: http://cordis.europa.eu/search/index.cfm
[Accessed 22 April 2013].
Doe, P., November 2012. *RapidResults - ADDITIVE MANUFACTURED PARTS IN USE TODAY.* [Online]
Available at: http://www.rapidnews.com/TCT-presentations-2012/DOE%20TCT%202012.pdf
[Accessed 23 April 2013].
EFFRA, 27 November 2012. *Factories of the Future Strategic Multi-Annual Roadmap - Validation Edition,* Belgium: European Factories of the Future Research Association - EFFRA .
EOS - e-Manufacturing Soluation, 2013. *Dental.* [Online]
Available at: http://www.eos.info/dental
[Accessed 22 April 2013].
European Commission, 2011. *Competitive Industries.* [Online]
Available at: http://ec.europa.eu/research/horizon2020/index_en.cfm?pg=competitive-industry
[Accessed 28 March 2013].
European Union, 13 March 2013. *Europe 2020 - Priorities.* [Online]
Available at: http://ec.europa.eu/europe2020/europe-2020-in-a-nutshell/priorities/index_en.htm
[Accessed 28 March 2013].
Fraunhofer-Gesellschaft, n.d.. *Regional structures with a global effect – the concept of innovation clusters.* [Online]
Available at: http://www.fraunhofer.de/en/institutes-research-establishments/innovation-clusters.html
[Accessed 22 March 2013].
Freedom of Creation, Powdered by 3D Systems, 2013. *Products - The award winning 3D printed design collection..* [Online]
Available at: http://www.freedomofcreation.com/collection/products
[Accessed 23 April 2013].

Gausemeier, J., Echterhoff, N., Kokoschka, M. & Wall, M., 2011. *Thinking ahead the future of Additive Manufacturing - Analysis of Promising Industries ,* Germany: Heinz Nixdorf Institute, University of Paderborn.
Gausemeier, J., Echterhoff, N., Kokoschka, M. & Wall, M., 2012. *Thinking ahead the future of Additive Manufacturing - Future Applications,* Germany: Heinz Nixdorf Institute, University of Paderborn.
Gausemeier, J., Echterhoff, N. & Wall, M., 2013. *Thinking ahead the Future of Additive Manufacturing - Innovation Roadmapping of Required Advancements,* Paderborn: Heinz Nixdorf Insitute, University of Paderborn.
General Electric (GE), November 20, 2012. *GE Aviation acquires Morris Technologies and Rapid Quality Manufacturing.* [Online]
Available at: http://www.geaviation.com/press/other/other_20121120.html
[Accessed 6 March 2013].
Hauser, C., 2012. *Laser Additive Manufacturing as a Key Enabler for the Manufacture of Next Generation Jet Engine Components - Technology Push,* s.l.: s.n.
Kirkely, J., September 26, 2012. *Additive Manufacturing is Ready to Rock and Roll.* [Online]
Available at: http://www.digitalmanufacturingreport.com/dmr/2012-09-26/additive_manufacturing_is_ready_to_rock_and_roll.html
[Accessed 7 March 2013].
Loughborough University , 2013. *Research.* [Online]
Available at: http://www.lboro.ac.uk/research/view/ss10/articles/weight-watchers/page3.html
[Accessed 29 April 2013].
Manufuture (CNR-ITIA), 2004. *Manufuture-EU.* [Online]
Available at: http://www.manufuture.org/manufacturing/
[Accessed 22 April 2013].
Martin, J., February 28, 2013. *Australian Additive Manufacturing Technology and Cooperative Research Roadmap.* [Online]
Available at: http://amcrc.com.au/aamtsummary
[Accessed 19 April 2013].
Martin, J., Posted on February 10, 2012. *New process to deliver efficiencies for aerospace.* [Online]
Available at: http://amcrc.com.au/microturbo_monash
[Accessed 23 April 2013].
Materials KTN, 2012. *Shaping our National Compentency in Additive Manufacturing - A Technology Innovation Needs Analysis Conducted by the Additive Manufacturing Special Interest Group for the Technology Strategy Board,* s.l.: Materials KTN.
MGX by Materialise, www.mgxbymaterialise.com, 2013. *Principal Collection: Lighting.* [Online]
Available at: http://www.mgxbymaterialise.com/principal-collection/lighting/family/list/list
[Accessed 23 April 2013].
Nike, Inc., 2013. *UNLEASH SPEED.* [Online]
Available at: http://www.nike.com/us/en_us/c/us-football/stories/2013/03/vapor-laser-talon
[Accessed April 2013].
President's Council of Advisors on Science and Technology (PCAST), July 2012. *Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing ,* s.l.: s.n.
Richardson, M. & Haylock, B., 2012. *Designer/Maker: The Rise of Additive Manufacturing, Domestic-Scale Production and the Possible Implications for the Automotive Industry,* s.l.: CAD Solutions, LLC, http://www.cadanda.com.
Scapolo, F., Churchill, P., Castillo, H. C. G. & Viaud, V., December 2012. *DRAFT FORESIGHT STUDY ON: "How will standards facilitate innovation an competitiveness in the European Union in the year 2025?",* s.l.: European Commission.
Scapolo, F., Churchill, P., Castillo, H. C. G. & Viaud, V., December 2012. *DRAFT FORESIGHT STUDY ON: "How will standards facilitate innovation and competitiveness in the European Union in the year 2025?",* s.l.: European Commission.

Scott, J. et al., March 2012. *Additive Manufacturing: Status and Opportunities,* s.l.: IDA - Science and Technology Policy Institute.
Shapeways, 5 March 2013. *Revealing Dita Von Teese in a Fully Articulated 3D Printed Gown.* [Online]
Available at: http://www.psfk.com/2013/03/dita-von-teese-3d-printed-dress.html
[Accessed 20 March 2013].
Shinbara, T., Posted 8 January 2013. Additive 101: A General Purpose User's Guide. *MTAdditive.*
Shipp, S. S. et al., 2012. *Emerging Global Trends in Advanced Manufacturing,* s.l.: IDA.
Sridhar, A., Attanasio, D. & Nannini, A., 2010. *Trends and Expertise Exchange within Rapid Manufacturing in Europe.* [Online]
Available at: http://www.rtejournal.de/ausgabe7/2377/view?set_language=en
[Accessed 19 April 2013].
Stratasys Ltd. , 2013. *Automotive Case Studies.* [Online]
Available at: http://www.stratasys.com/resources/case-studies/automotive/bmw
[Accessed 24 April 2013].
Stratasys Ltd, 2013. *Automotive Case Studies.* [Online]
Available at: http://www.stratasys.com/resources/case-studies/automotive/joe-gibbs-racing-filter
[Accessed 23 April 2013].
Technology Strategy Board, 29 October 2012 . *£7 million investment to promote innovation in additive manufacturing.* [Online]
Available at: http://www.innovateuk.org/content/press-release/7-million-investment-to-promote-innovation-in-addi.ashx
[Accessed 28 March 2013].
The British Standards Institution, 2013. *Committee: AMT/8 Additive manufacturing.* [Online]
Available at: http://standardsdevelopment.bsigroup.com/Home/Committee/50226095#tabs-representation
[Accessed April 2013].
The Lund Declaration, July 2009. *The Lund Declaration - EUROPE MUST FOCUS ON THE GRAND CHALLENGES OF OUR TIME,* s.l.: s.n.
Tomlin, M. & Meyer, J., 2011. *Topology Optimization of an Additive Layer Manufactured (ALM) Aerospace Part.* s.l., Altair Engineering.
UK Parliment, 2009. *Stimulating Innovation.* [Online]
Available at:
http://www.publications.parliament.uk/pa/cm200910/cmselect/cmneast/169/16908.htm
[Accessed March 2013].
United States Department of Commerce - Commerce.Gov , Submitted on August 15, 2012 - 2:00pm . *Fact Sheet: Additive Manufacturing.* [Online]
Available at: http://www.commerce.gov/news/fact-sheets/2012/08/15/fact-sheet-additive-manufacturing
[Accessed 7 March 2013].
Watson, S., March 2012. *3D PRINTING IS MERGED WITH PRINTED ELECTRONICS.* [Online]
Available at: http://www.optomec.com/site/latest_news/news95
[Accessed April 2013].
Wohlers Associates, Inc., 2011. *Additive Manufacturing Technology Roadmap for Australia,* Fort Collins, Colorado 80525 USA: Wohlers Associates, Inc..
Wohlers, T., 12 April 2012. Additive Manufacturing in the United States. *TCT magazine,* p. 29.
Wohlers, T., 2012. *Wohlers Report 2012 - Additive Manufacturing and 3D Printing State of the Industry: Annual Worldwide Progress Report.* 2012 ed. Colorado, USA: Wohlers Associates .
www.ukparliment.co.uk, Prepared 20th April 2012. *Bridging the Valley - Written evidence submitted by Rolls-Royce (V85).* [Online]
Available at: http://www.publications.parliament.uk/pa/cm201012/cmselect/cmsctech/writev/valley/valley85.htm [Accessed April 2013].

ACKNOWLEDGEMENTS

The AM Sub-Platform would like to express sincere thanks to the individuals that have contributed to this report, and who took part in interviews and/or provided written statements:

- Anna Hoiss - DSM
- Brent Stucker - University of Louisville
- Emma Ashcroft - TWI
- Eric Klemp - DMRC
- Frits Feenstra - TNO
- Gideon Levy - TTA (Technology Turn Around)
- Jan Sehrt - University of Duisburg
- Jörg Lenz - EOS
- Magi Galindo I Anguera - Leitat
- Marina Wall - Heinz Nixdorf Institute, University of Paderborn
- Martin Schaefer - Siemens AG
- Martin Baumers - Nottingham University
- Olivier Jay - Teknologisk Institut
- Pentti Eklund - VTT
- Phil Reeves - Econolyst Ltd
- Robert Scudamore - TWI
- Tom Craeghs - Materialise

Other experts provided information and ideas through the AM Sub-Platform meetings and/or links to AM specific information. Use of publications, data and reports available in the public domain were also used within the report.

Key Editors:

Amanda Allison
TWI Ltd

Robert Scudamore
TWI Ltd

Consultation

This document is a live document which is continually open to the AM community for review in order that all relevant Stakeholders have the opportunity to express their suggestions for improvement, identify other essential recommendations or provide general comments. This input will be progressed and will result in a further validated version of the SRA.

Please direct responses to:

Amanda Allison (amanda.allison@twi.co.uk)

Further updates will be provided at www.AM-platform.com