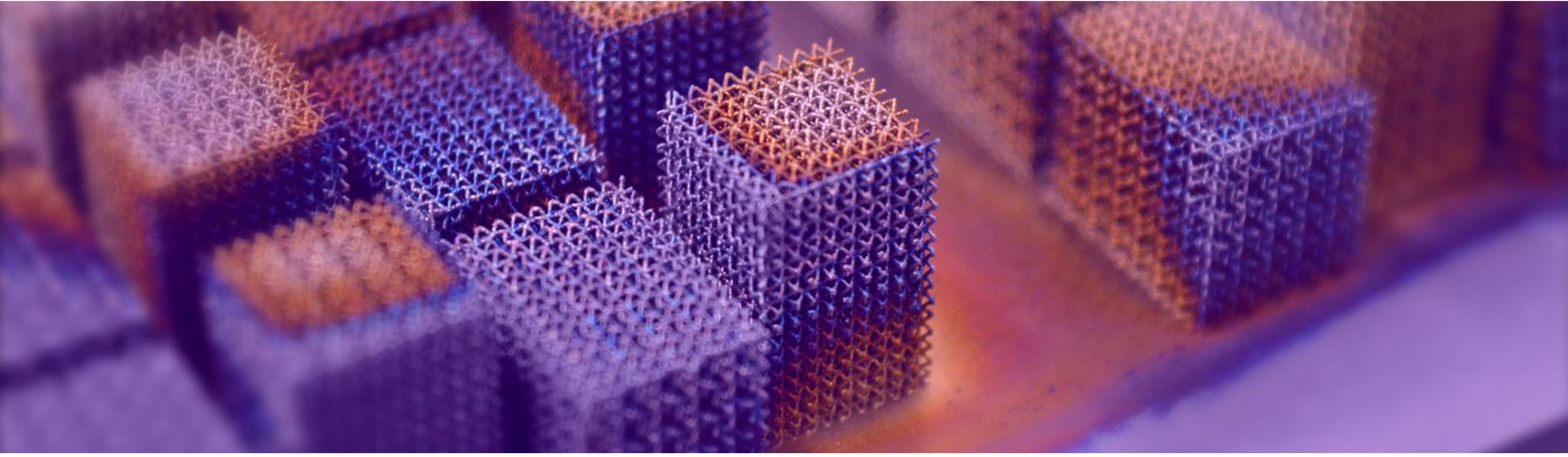


THE CURRENT LANDSCAPE FOR ADDITIVE MANUFACTURING RESEARCH

A review to map the UK's research activities in AM internationally and nationally

2016 ICL AMN report

Dr. Jing Li
Dr. Connor Myant
Dr. Billy Wu

Imperial College Additive Manufacturing Network

Imperial College London

Contents

List of Definitions/ Nomenclature

2PL	Two Photon Lithography
ABS	Acrylonitile butadiene styrene
AM	Additive manufacturing
BAAM	Big area additive manufacturing
BJ	Binder jetting
CAD	Computer aided design
CAGR	Compound average growth rate
CBJ	Ceramic Binder Jetting
CLIP	Continuous light interface production
CNC	Computer numerically controlled
DED	Direct Energy Deposition
DIY	Do it yourself
DMLS	Direct metal laser sintering
DSTL	Acrobat Distiller
EBAM	Electron beam additive manufacturing
EBM	Electron Beam Melting
EPSRC	Engineering and Physical Sciences Research Council
EU	European Union
FDM	Fused deposition modelling
HSS	High Speed Sintering
HVM	High Value Manufacturing
ICL	Imperial College London
IP	Intellectual property
IS	Infrared sintering
LMD	Laser Metal Deposition
LMJ	Liquid Metal Jetting
LU	Loughborough University
MBJ	Material Binder Jetting
ME	Material Extrusion
MJ	Material Jetting
MMJ	Multi Material Jetting
MTC	Manufacturing Technology Centre
MWF	Metal Wire Feed
OEM	Original equipment manufacturer
OIJ	Organic Ink Jetting
PBF	Powder bed fusion
PIJ	Polymer Ink Jetting
PJ	Polymer Jetting
PLA	Polylatic acid
PWC	PricewaterhouseCoopers
RCUK	Research Council UK
RDM	Redistributed manufacturing
ROW	Rest of the world
RP	Rapid prototyping
SIG	Special Interest Group
SLA	Sterolithography
SLM	Selective laser melting
SLS	Selective laser sintering
SMD	Shaped Metal Deposition
STL	Stereolithography File Format
TRL	Technology Readiness Level
TWI	The Welding Industry
UAM	Ultrasonic Consolidation
UK	United Kingdom
UOC	University of Cambridge
UON	University of Nottingham
UCL	University College London
UOS	University of Sheffield
US	United States
Vat-P	Vat-photo Polymerisation
WAAM	Wire and arc additive manufacturing
WIJ	Wax Ink jetting

Version 1.0

Executive Summary

This report outlines the current status of additive manufacturing (AM) research internationally and nationally, with a focus on the strengths, weaknesses, opportunities and threats posing UK AM research.

AM is a technique which enables the creation of complex 3D objects, previously not possible with traditional subtractive manufacturing. It has been identified by the government as one of the key technologies required to enable high value manufacturing in the UK. The technology has in recent years entered into applications such as medical, aerospace and automotive due to innovations in materials and processing technologies, yet there are still many technical challenges that must be overcome in order to achieve a higher market penetration. With regards to materials processing and printing technologies, these have been identified as:

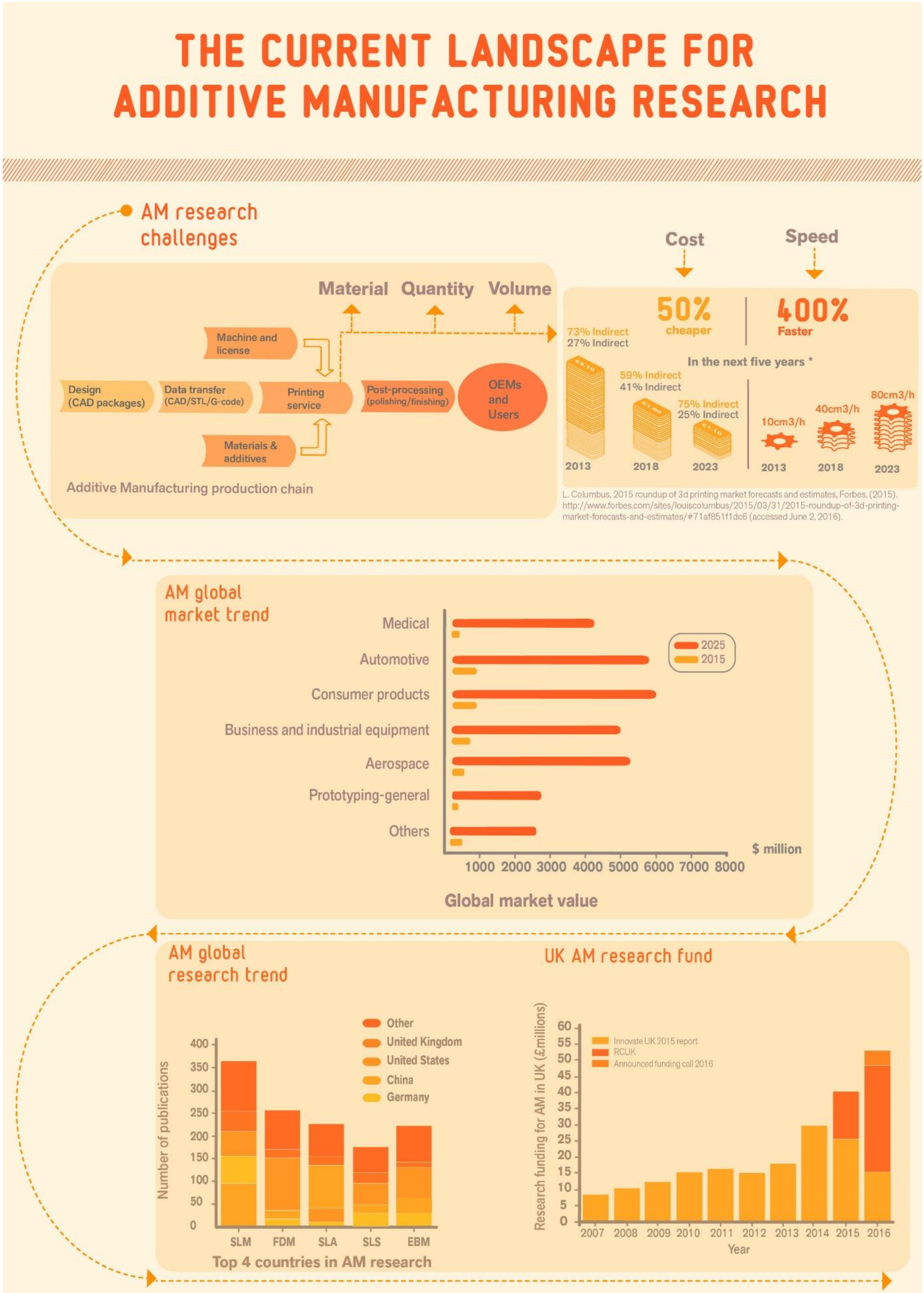
- The need to increase dimensional accuracy and repeatability of parts potentially through in-situ metrology and combined model based approaches.
- Limited material options necessitating the need for new materials.
- Methods which enable cost reductions and increase build speed, and size, of parts.

However, beyond the machines, there are also many research challenges that need to be addressed across the production chain that are often overlooked, including:

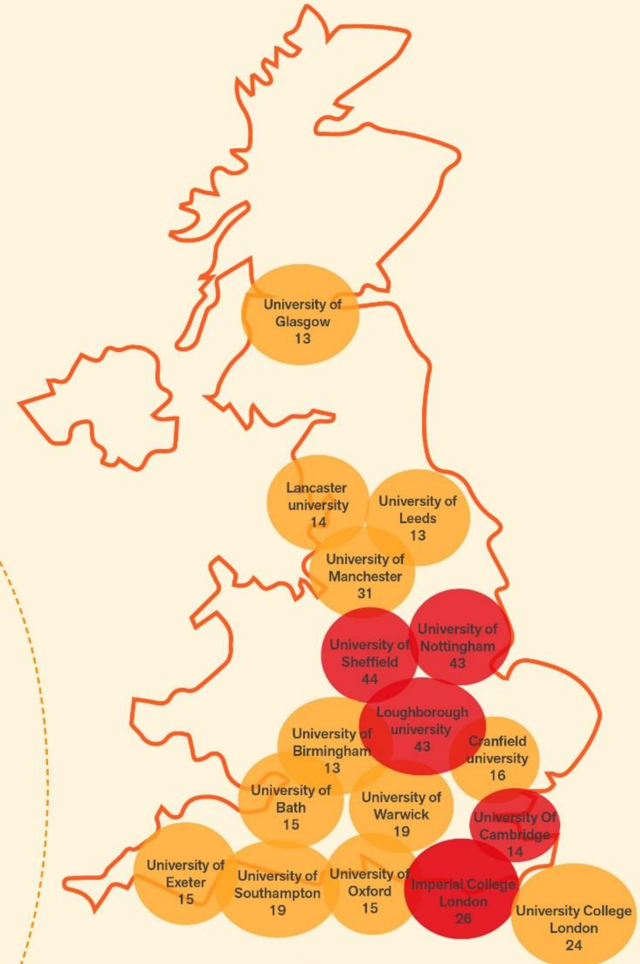
- Improved software tools which are capable of handling the geometric complexities of designed components.
- Supporting design tools and methodologies which aid with the design for AM process to unlock the true potential of the technology.
- The need for improvements in the pre- and post-processing technologies and approaches.
- Limited work relating to digital ownership and standardisation.

Globally, the UK is within the top 4 countries working on additive manufacturing; accompanied by the US, China and Germany. Within the EU, AM is clearly a priority area with €160 million worth of research funding invested, much of which the UK is involved with [1]. In the UK, the current EU funding in AM currently represents 18% of available funds and with the UK's decision to leave the EU, it is important to ensure that future research funds are secured to ensure the health of this research area. In the UK, there are research activities across the various additive technologies, with more of a focus on low-mid technology readiness level (TRL) works. However, whilst there is this focus on novel technologies the translation of this research into commercial impact has, thus far, been limited and there is a need to bring together the excellent fundamental science base in the UK with the industrial applications in AM.

Funding within the UK has been shown to exhibit a long tail effect, with a small number of institutions, mainly in the Midlands, receiving the majority of the research funding, though there are signs that this is shifting. Whilst, there is a healthy amount of industrial engagement, there is also evidence that there is limited cross-pollination of research activities. Thus, the UK has been shown to have significant capabilities in additive manufacturing, however the need for improved collaboration has been identified on top of the research challenges.

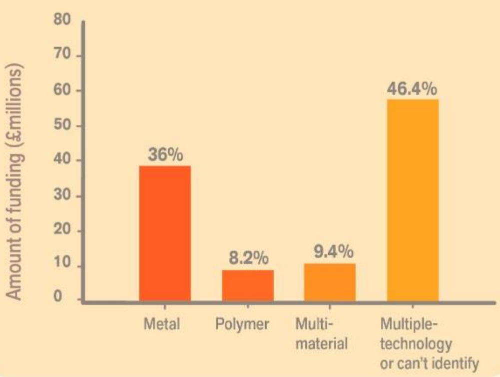

THE CURRENT LANDSCAPE FOR ADDITIVE MANUFACTURING RESEARCH
AM research challenges
Material
Quantity
Volume
Machine and license
Design (CAD packages)
Data transfer (CAD/STL/G-code)
Printing service
Post-processing (polishing/finishing)
OEMs and Users
Materials & additives
Additive Manufacturing production chain
Cost
Speed
50% cheaper
400% Faster
73% Indirect
27% Indirect
In the next five years *
59% Indirect
41% Indirect
75% Indirect
25% Indirect
2013
2018
2023
10cm3/h
40cm3/h
80cm3/h
2013
2018
2023
L. Columbus, 2015 roundup of 3d printing market forecasts and estimates, Forbes. (2015). http://www.forbes.com/sites/louiscolumbus/2015/03/31/2015-roundup-of-3d-printing-market-forecasts-and-estimates/#71af851f1dc6 (accessed June 2, 2016).
AM global market trend
Medical
Automotive
Consumer products
Business and industrial equipment
Aerospace
Prototyping-general
Others
2025
2015
1000 2000 3000 4000 5000 6000 7000 8000
$ million
Global market value
AM global research trend
Other
United Kingdom
United States
China
Germany
Number of publications
0 50 100 150 200 250 300 350 400
SLM FDM SLA SLS EBM
Top 4 countries in AM research
UK AM research fund
Innovate UK 2015 report
RCUK
Announced funding call 2016
Research funding for AM in UK (£millions)
0 5 10 15 20 25 30 35 40 45 50 55 60
2007 2008 2009 2010 2011 2012 2013 2014 2015 2016
Year

Geographic distribution of academic AM research in UK

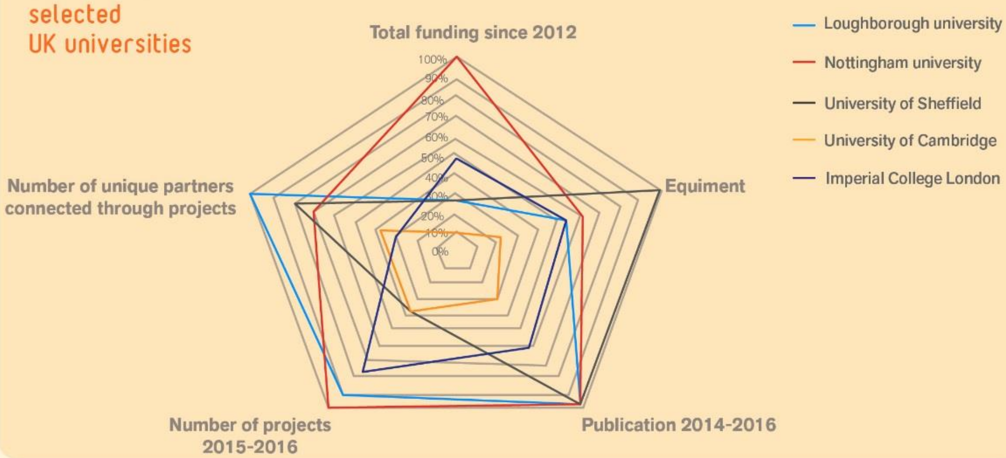


Five selected UK universities for in-depth analysis in AM research

Total funding per material type in the UK



Overview of 5 selected UK universities



1. Introduction

AM has been identified as being one of the key enabling technologies for the development of high value manufacturing in the UK [1]. In 2015, the industry was valued at $5.9 billion with 93% of this attributed to industrial applications. Previous applications of the technology have been limited to rapid prototyping, however with advances in the technology, the uptake of AM in industries such as aerospace, automotive and medical has seen a significant increase. Yet, this market penetration is still limited and key challenges in terms of process speed, improving material properties and lowering overall cost still remains.

Therefore, in order to enable high value manufacturing in the UK, research in universities needs to be aligned to address these key challenges. This report outlines the current status and key challenges in AM, internationally and nationally with a focus on informing a potential future research roadmap. This report is broken down into the following sections:

Chapter 2: Want is additive manufacturing?

- Presents the broad AM technology areas focusing on their strengths, trends and challenges still yet to be solved.

Chapter 3: Mapping additive manufacturing research activities internationally

- An overview of the current global AM market and research trends.
- The evaluation on AM markets analyses the market-segment values, growth, machine sales, and geographic trends.
- The global research trends are studied by identifying the overall trends, top organisations and research focus on AM technologies.

Chapter 4: Mapping AM research activities nationally

- In order to evaluate the strength and impact of the UK's AM research globally, this chapter examines the AM research nationally. This will identify the strengths and limitations of the current UK research, and recognise the current or merging gaps in the research base nationally.
- By looking into various AM projects and publications, this chapter reviews the overall research trend, amount of funding and identifies the top and emerging organisations, geographic distributions and technology focus in AM research.

Chapter 5: Detailed analysis on leading UK universities

- This chapter presents an in-depth analysis on AM research for 5 selected UK universities, including: University of Nottingham, Loughborough University, University of Sheffield, University of Cambridge and Imperial College London.
- The capabilities of each university is assessed by publically available information on its equipment, amount of funding and focus in research topics.

Chapter 6: Conclusions

- Concluding remarks on all the presented information and suggested paths for progression, improvement and expansion of UK academic AM research activities.

2. What is additive manufacturing?

AM is a technique for creating complex geometries, not possible with traditional subtractive manufacturing, directly from computer designs through the sequential solidification of layers of material. The technology was originally limited to model making and prototyping applications due to insufficient mechanical properties and resolution. However, with advances in materials processing, the application of the technology has expanded into areas such as medical, aerospace and automotive, to name but a few.

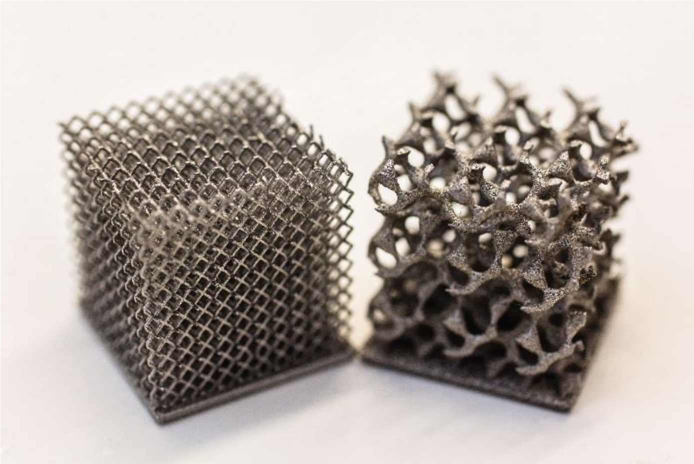


Figure 2-1: Metal lattices made with Direct Metal Laser Sintering. Credit: Billy Wu

2.1. Advantages of additive manufacturing

As a “tool-less” and digital approach to manufacturing, AM offers an extensive and expanding range of social, economic and technical benefits. The main benefits include:

- AM affords designers a **freedom in geometric complexity** previously unavailable to them, and the freedom of variety to manufacturers as tooling changes are no longer required between design updates. Paired with computer-aided design (CAD) software, AM techniques enable the creation of new types of objects with unique material and structural properties, e.g. lattice structure or topologically optimised structure to increase functionality and performance of a product.
- **Construction periods and cost can be dramatically reduced** as AM offers the opportunity to eliminate production processes, assembly steps, and the reliance on skilled technicians.
- **Low volume production** and **mass personalisation**: e.g. personalised hearing aids and implants at reasonable cost.
- The step change from subtractive manufacturing process significantly **reduces material waste** and environmental impact. e.g. aerospace and automotive industries are using AM to reduce weight and improve the fuel efficiency of their engines.
- AM also encourage the emergence of **distributed manufacturing** and new supply chains, as consumers can now engage in the design of products. These products can then be manufactured at a location close to the consumer, instead of in a centralised factory.

AM offers greater product and process benefits compared to traditional manufacturing systems; but it is not a universal cure-all process to replace today's subtractive manufacturing methods as there remains significant technology challenges to address.

2.2. Types of additive manufacturing technology and challenges

Whilst there are new AM techniques continually being invented, there are seven main process categories. This was classified by the American Society for Testing and Materials (ASTM) group, as shown in Table 2-1. Many other manufacturing approaches can claim to be AM, such as carbon composite layup production, but will not be included in this study based on the ASTM standard. Table 2-1 shows a summary of currently available/developing AM technologies to highlight the current applied techniques and the materials they utilise. It is clear from this overview that from a materials perspective, **polymers are the most developed due to the ease of manufacturing. Development of engineering grade materials such as metals is currently driven by high-end industrial needs in applications such as aerospace, medical and motorsports.** Other materials such as ceramics, composites and biological are more limited due to the currently lacking industry pull.

Table 2-1: Summary of broad 3D printing technologies

	Technologies						
Materials	Powder bed fusion	Direct energy deposition	Material jetting	Binder jetting	Material extrusion	Vat photo-polymerisation	Sheet lamination
Polymers							
Metals							
Ceramics							
Composites							
Biological							

Not currently developed		In R&D stage		Commercially available	

Powder Bed Fusion (PBF): This process uses thermal energy from a laser or electron beam to selectively fuse powder in a powder bed.
Directed Energy Deposition (DED): Utilizes thermal energy, typically from a laser, to fuse materials by melting them as they are deposited.
Material Jetting (MJ): This process, typically, utilizes a moving inkjet-print head to deposit material across a build area.
Binder Jetting (BJ): This process uses liquid bonding agent deposited using an inkjet-print head to join powder materials in a powder bed.
Material Extrusion (ME): Push material, typically a thermoplastic filament, through a nozzle onto a platform that moves in the x, y, z plane.
Vat Photopolymerization (Vat-P): These machines selectively cure a liquid photopolymer in a vat using light.
Sheet Lamination (SL): This process uses sheets of material bonded to form a three-dimensional object.

To expand on this, Table 2-2 articulates the process associated with several selected technologies as well as some of the associated challenges.

Table 2-2: Description of some of the common and emerging 3D printing technologies

Technology	Description	Research challenges
Fused deposition modelling (FDM) Material extrusion	• Polymer filament is extruded through a hot nozzle. • Commonly processed materials include: ABS, PLA, Nylon, flexible polymers, conductive polymers with emerging materials including: ceramic, metal and composite filled materials. • Cost is relatively low and can be relatively easily scaled from desktop units to large scale printers capable of making structures like cars.	• Surface quality is poor due to the appearance of filament striation. • Limited mechanical strength, due to factors such as delaminating layers caused by inconsistent adhesion of filament layers. • Support structures for FDM printing have largely remained un-optimised, wasting material and increasing print times.
Stereolithography (SLA) Vat photo-polymerisation	• Uses a laser to polymerise and solidify liquid resins. • Materials include propriety polymeric materials and some attempts into processing ceramic components (e.g. Alumina, zirconia) via post-treatment techniques. • Relatively low cost and typically higher resolution than FDM.	• Parts are photo-sensitive after curing and can become brittle if suitable surface treatments are not provided. • Peeling mechanisms can cause damage to fine details on parts further reducing the practical resolution. • Removal of resins from parts can be a challenge with fine details and high viscosity monomers.
Selective laser sintering (SLS) Powder bed fusion	• Uses a high power laser to selectively sinter polymer powder. • Commonly processed materials include: nylon and polyamide. • No support material required, with better build quality than FDM and reasonable mechanical strength.	• Porosity in parts can result in mechanical properties of parts which are below their bulk properties. • Post processing in terms of powder removal is time consuming and the recovery rate of material is not 100%. • Technology cost is relatively high compared to FDM and SLA.
Direct metal laser sintering (DMLS) Powder bed fusion	• Uses a high power laser to selectively melt metal powder. • Commonly used materials include: stainless steel, cobalt chrome, titanium and aluminium. • Parts have engineering grade strength.	• Cost of the equipment is high due to the need for an inert atmosphere and high power lasers. • Surface quality and dimensional accuracy are still limited resulting in the need for post-machining. • The high temperature melting process results in considerable thermal stresses which can cause dimensional inaccuracy and failure of parts. • Significant support material is required to ‘pin-down’ parts increasing the post-processing requirements and decreasing the material recyclability.
Polymer jetting (PJ) Material jetting	• Polymer inks are jetted out and cured by an overhead UV lamp. • Propriety polymeric materials. • Parts typically have high resolution and can be multi-material. • The support material is dissolvable which reduces the manual element of support removal.	• Some attempts in ceramic, metals and semiconductors development to create parts with added function, but due to limitation in viscosity of processing fluid, results in a relatively low concentration of solid particles. • Costs are relatively high in comparison with FDM and SLA.

Continuous liquid interface production (CLIP) Vat photo-polymerisation	• A 2D slice is simultaneously printed in liquid resin. • Extremely high print speeds can be achieved due to the removal of the 'peeling' process through the use of an oxygen permeable membrane which creates a 'dead-zone'. • Excellent resolution.	• Currently materials are limited to polymeric materials, the majority of which are proprietary. • Current costs are high.
2-photon polymerisation Vat photo-polymerisation	• Uses 2-lasers to polymerise and solidify liquid resins. • Highest resolution in class (can create structure down in the nanometer length scale).	• Limited and propriety polymeric materials. • Limited scale of parts. • High cost of system.
Bioprinters Material extrusion	• Extrudes biomaterials in a similar way to FDM.	• Limited and propriety biomaterials. • Limited resolution. • High cost of system.
Metal jetting Material jetting	• Jets out molten metal droplets in specific locations to create the desired metallic 3D geometry.	• Corrosion of the print heat with the molten metal. • Formation of oxides between layers reducing mechanical strength of parts.

Currently available		Near term		Long term	

2.3. The manufacturing production chain and challenges

Despite in-roads in technology adoption into new industries, the uptake of AM is still limited due to technological challenges, not just with the AM printing equipment but with the entire value chain. Figure 2-2 highlights the key elements of this manufacturing system to be considered.

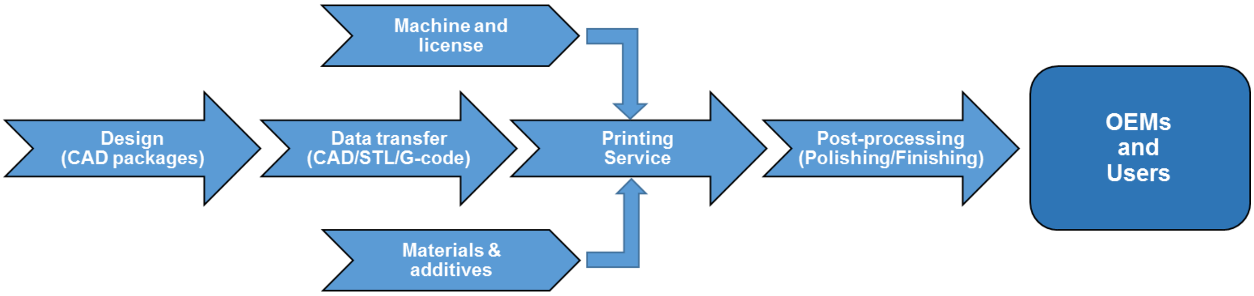


Figure 2-2: AM production chain

A number of factors that currently hold back widespread AM adoption include:

- **The printer can create virtually any geometry but our software tools are lagging behind**

CAD software packages were born out of the CNC revolution of the 1980s. There is not, as yet, a widely available, intuitive and comprehensive CAD software package developed specifically for AM. This means that AM design engineers have to learn their trade through a mainly trial and error process; coming at potentially great cost and time to their business. Improved CAD and new generations of AM trained design engineers on undergraduate course, will do a lot to help AM market expansion.

One of the advantages of AM is the ability to create complex 3D geometries such as lattice structures. However, whilst the equipment may be able to create the geometries, the computational models which describe them are lagging behind. Conventionally, 3D models are described using the STL file format which approximates a structure into a series of triangulated surfaces. For simple structures this is acceptable, however for complex lattices which can have millions of surfaces, the file size quickly becomes unmanageable and therefore there is a need to develop new software tools and file formats which enable more efficiency description of lattice geometries.

In addition to this, without the limitations imposed by traditional subtractive manufacturing, the possibilities of augmenting device design have been unlocked. However, tools that enable design for AM have lagged the technology and thus there needs to be a renewed emphasis on the development of these design tools.

- **What you design, and what you get are not always the same**

Mismatch between design and build, not to be confused build quality. This refers to issues in data management and data translation between CAD packages and tool path codes used by printing machines. As yet there is no universal market standard for data transfer/translation, which ultimately leads to build errors created by incorrect/corrupted data. Many high end AM machines, for example, use their own proprietary file format which compounds the possible data transfer problems.

- **Quality and repeatability are still a question mark**

Many industries feel that quality and repeatability of AM parts is not good enough to meet their particular market/consumer standards or, in sectors such as aerospace, not able to meet the strict safety standards. The poor build quality is partly due to the infancy of AM and AM machine builders.

Powder bed technologies have in particular gained traction in industrial grade applications due to end components having engineering level performance. However, in thermal based processes such as DMLS, the residual stresses imparted onto the component due to the melting process can cause dimensional inaccuracies. Compounded with variations in the particle size distribution and oxidation state of the powders, this can result in quality and repeatability issues. Some researchers have begun to address this by incorporating in-situ monitoring of the build process and developing physical models of the printing process but linking the two together remains a gap in research which could yield significant gains in performance and repeatability.

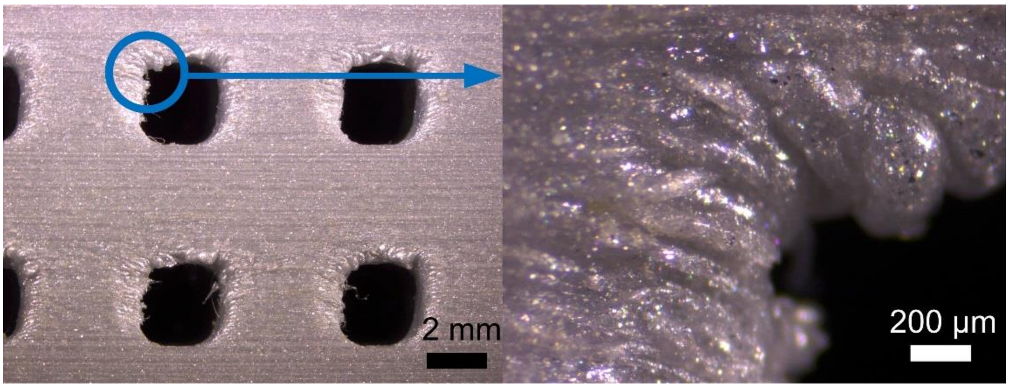


Figure 2-3: Optical image of Fused Deposition Modelling part showing layering and dimensional inaccuracies of a desired square hole. Credit: Billy Wu

- **3D printers are getting faster but the manual pre- and post-processing is lagging**

Whilst AM is not likely to become a mass production method in the near future, build speeds are still an important aspect. However, for many applications, build speed is still comparatively slow compared to traditional manufacturing techniques. Therefore, the part cost economies do not encourage manufacturers, designers, and business to switch production methods to AM. The best example of this is when comparing AM parts to injection moulded parts, however there is the case to be made for AM making traditional manufacturing mode flexible, for example 3D printing of injection moulding tools. With regards to improvements in print speed from a machine perspective, researchers are investigating optimised scan patterns, multi-print head systems and adaptive print conditions such as variable layer heights.

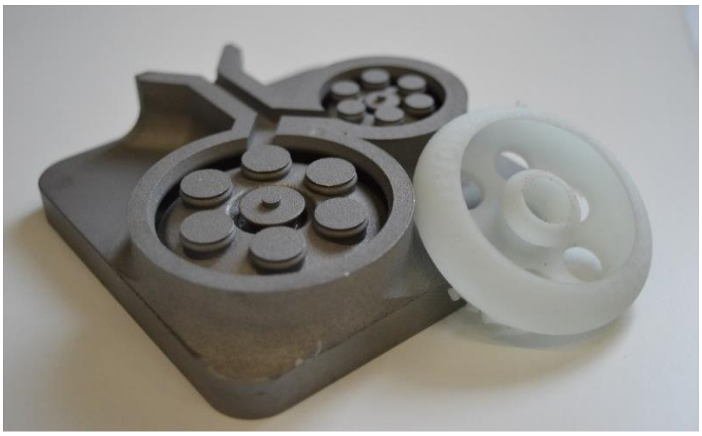


Figure 2-4: Injection moulding tool made with direct metal laser sintering. Credit: Nate Petre

Whilst improvements in the machine and printing process, which has received the most attention, will inevitably improve build speeds, the pre- and post-processing of parts both digitally and physically is often an overlooked area of work. For example some progress has been made in topological optimisation tools which can help to automate the design process, however these currently require considerable computational effort and user experience to set-up. This design process can in many cases take much longer than the print and post-processing stages.

On the post-processing aspect, depending on the AM method, labour intensive processes such as: heat treatment, support removal, part removal from base plate, cleaning, powder sieving and many others can be a significant logistical and financial burden that is often overlooked. Innovations in automation or time reduction of these processes will be important. This is often linked to effective pre-processing, for example optimised support structure design.

- **Design for AM is still an art rather than a science**

Prints can fail for multiple reasons, from designer error to machine fault. Machine errors typically relate to the ability/quality of the printer and data transfer. As equipment and software developers progress failure rates will drop. However often multiple, different, parts are printed simultaneously to reduce time and costs, this can introduce further complexity and changes to the print conditions. Additionally, data transfer is another cause for build failures as each print machine uses a bespoke code dependent on the manufacture. Errors created when CAD files are converted into the machine code cause the large majority of failures. Designer errors, are due to parts being created which are not well optimised for the manufacturing technology. Improved tools to aid in the set-up of files is therefore needed to reduce the number of failed builds which inevitably increases cost.

- **3D printing does not actually removal all material waste**

One of the most common environmental claims is that AM produces less waste than traditional manufacturing technologies. In most cases this is valid. However, material waste is not completely removed and can be created by failed prints, build support structures and degraded material. Support structures are vital for many AM techniques to support the object mass during the build and to act as a thermal sink. All this material could amount to the same mass (or more) than the actual printed part. Currently, the majority of this waste material cannot be re-cycled. For example, Inkjet systems waste around 40% of their ink during a print, not including support material [2]. At the industrial scale, 3D printers that use powdered or molten polymers leave behind a substantial amount of raw material in the print bed. This unused material is typically not reused because its properties have been compromised. Commonly used direct metal laser sintering machines also use only part of the metal in their powder beds. Good prints require a ratio of additional virgin material to previously used powder to avoid problems, so a significant amount of waste is generated with each build.

- **Everyone has their way of doing it**

Since the inception of AM, manufacturers have been fragmented. Figure 2-2 highlights the various stakeholders in the AM value chain. It is evident from the presented information that many AM technologies exist and that IP protection is rife. Thus, industry standards are yet to be widely adopted. This lack of standards can lead to significant variations in product quality and difficulties in translating between stakeholders in the value chain.

- **Things are virtually all virtual**

Digital ownership of product designs, specifications and technical information for items is now of critical importance with a digitized manufacturing method. Through a combination of AM and the increasing available access to digital information, files, and designs, the value chain has shifted from the physical object to its digital design. The idea is that AM gives consumers the ability to build products (at home) anywhere, whenever they want; as long as they have the design data. This is creating fear within industries of piracy. How to protect the digital information is an area of great concern. Similarities can be made with the music industry during the 90s and 00s. Conversely, this could also open new markets for service providers on similar models to Spotify and iTunes. Yet, policies around digital ownership of objects has lagged behind and needs to be addressed in the near future.

2.4. Conclusions

AM covers a broad range of different techniques, classified by the means by which material is deposited and solidified. Due to ease of manufacturing, polymers have seen the most widespread application, however this is rapidly growing to include more materials such as metals, ceramics and composites. However, whilst penetration of the technology into fields such as aerospace, automotive and medical have seen increases in recent years, mass market penetration has still yet to be achieved due to a number of technical challenges.

Research and industry challenges therefore include:

- Inconsistent repeatability of prints compounded by requirements for better material properties.
- Largely un-optimised support structures which adds printing time and cost.
- Software tools which are unable to describe the complex geometries that the AM equipment is capable of.
- Lack of universally adopted standards, which results in a mismatch between what you design and what you get.
- Lengthy and costly pre- and post-processing steps in the AM production chain such as model set-up, support removal and material recycling.
- Limited availability of design for AM tools which enable “non-experts” to gain the maximum benefit of the technology.
- Unclear and limited frameworks regarding digital ownership of models.

Therefore, to address these challenges innovations in the whole process chain are required with academic research a potential pipeline for solutions.

3. Mapping the international additive manufacturing research landscape

Innovations which start at the fundamental research level have resulted in the progression of AM as purely a rapid prototyping technology into one which is beginning to see application in engineering applications due to improvements in the materials available.

The aim of this chapter is to conduct a review on the global AM market, as market trends are used as an indicator for growth in AM academic research. The current international research landscape is then assessed in terms of areas of study, level of activity and geographical trends.

3.1. Global market trend

3.1.1. Growth in market value

The global AM market, consisting of all AM products and services worldwide, is on the rise. As reported in the 2014 Wohlers report [3], the global AM market has grown substantially by nearly five-fold over the past six years. AM has indeed come a long way over the last decade, but it still only represents 0.02% of global manufacturing activities in 2015, which was about $25 trillion in 2014 [4]. The global need for 3D printers is expected to grow by over 40% in the following 10 years, as more manufacturing sectors adopt its benefits. At the same time, the average price per printer is forecasted to drop, thus **the global market value is expected to rise to $21 billion in 2020 with average CAGR close to 30%** [3]**. The Sustained double digit growth in AM global market will drive to overcome AM technical and commercial barriers.**

With consideration of the AM market, this can be divided into two main subcategories:

- **The industrial market**: this includes users from commercial enterprises, ranging from larger scale (e.g. Airbus for components in their plane) to smaller scale (e.g. Beltone for its high valued hearing aids). These users will typically buy more advanced industrial AM systems that sell for $5,000 or more.
- **The DIY consumer market**: the users are small residential consumers or hobbyists who will normally buy home desktop systems under $5,000. The academic researchers utilise both industrial and desktop AM machines to conduct AM research.

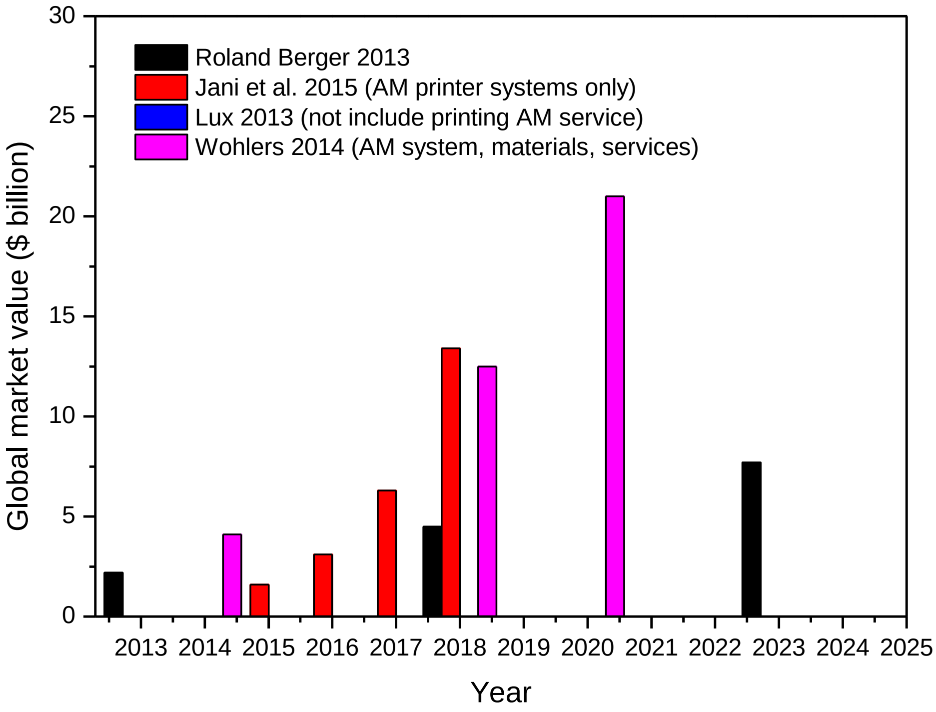


Figure 3-3: Projected global 3D printing market value from 2012 to 2025 [5–8]

3.1.2 Additive manufacturing growth in industrial markets

Figure 3-4 shows more clearly the magnitude of the global AM growth in each segment of industrial markets. The top 5 segments of global AM market in 2015 were automotive, consumer products, business and industrial equipment, aerospace and prototyping [4]. It is worth mentioning that the medical related markets have been divided into three sections here for comparison and the market value for this whole category will add up to $330 million in total in 2015 [4], which is significantly higher than the individual markets.

In the next 10 years, the AM industry will continue its high growth rate, with CAGR ranging from 18% (Academics & Education) to 36% (Medical prosthetic device) for different market segments [4]. The primary markets will maintain their strength, but aerospace is likely to catch up faster and ranked as the third. The highest value market will continue to be automotive with $7,036 million, then followed with consumer products, aerospace, business and industrial equipment and prototyping. The top 3 fastest growing segments are related to medical applications, 27.3% for medical and dental, 28.2% for medical and dental diagnostic and treatment, 36.4% for medical prosthetic device [4].

The UK will follow the overall rising global trend, with aerospace (e.g. satellite application, parts production), healthcare/medical (e.g. orthopaedic implants, dental crowns) and creative industries (e.g. tailored jewellery and furniture) and motorsport sectors as most active in using AM technology [9]. The products under development are being tested in niche applications or being sold on small scale. Energy generation and the reminder of the automotive sector are less proactive, for example in power generation, gas turbine manufacture are happy to follow the lead of aerospace gas turbine technology research in the field of AM [9].

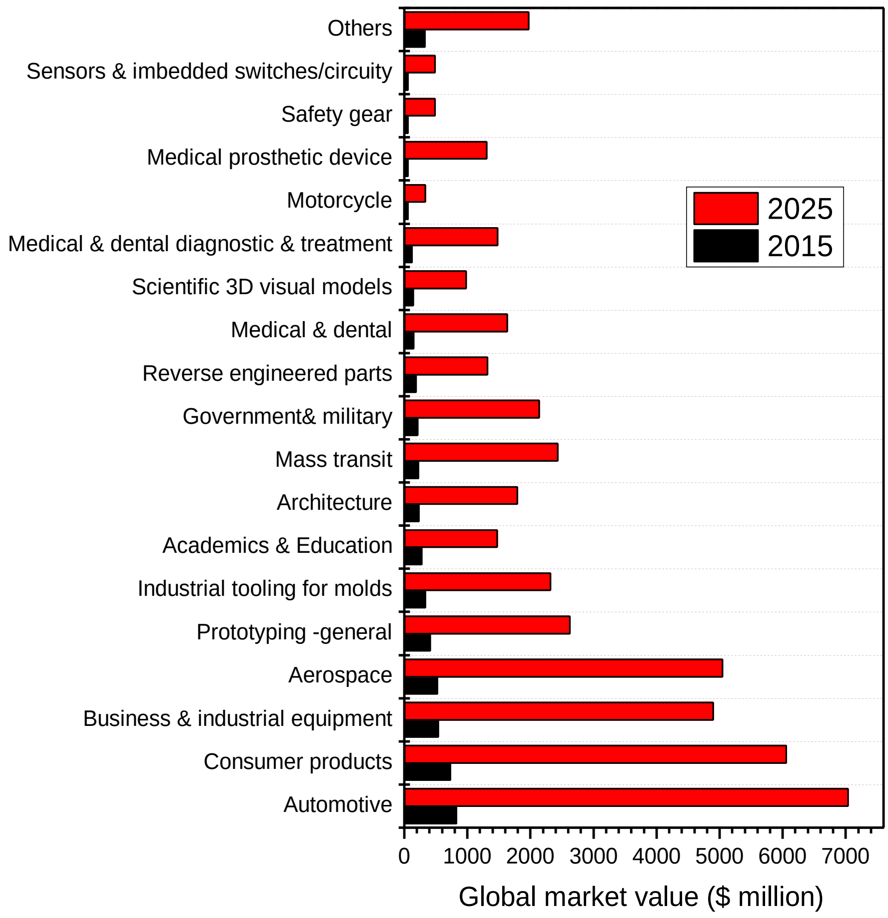


Figure 3-4 Projected global industrial AM market by application from 2015 to 2025 [4]

3.1.3 Geographic trends

AM is a global phenomenon, but the value across regions varies, with 41% from North America, 30% from Europe, 25% from Asia and 4% from the rest of the world (ROW) [4]**.** In 2025, North America is anticipated to drop to 37% of the 3D printer market, with Europe and China with faster growth rate increasing to 32% and 29% respectively. Then the rest of the world in 2025 will be at 2% [4].

3.2 Global research trend

3.2.1 What is the overall trend throughout years?

The earliest research on AM started from 1960s with only a few publication found over decades, following with two early key patents on SLA and FDM filed in 1980s. As some IP started to expire since 2000, AM techniques have started to attract a lot of interest from industry, leading to a substantial growth in AM related research, thus the number of AM publication have increased exponentially to over 3,000 globally in 2015 (Figure 3-5) [10–12]. The data in this section is gathered using Scopus as a search tool and the criteria can be found in Appendix 9.1. **Given that the global market is escalating at double digit growth rates after 2015, the exponential growth in AM publication is expected to continue in 2016 and afterwards** [3–5]**.**

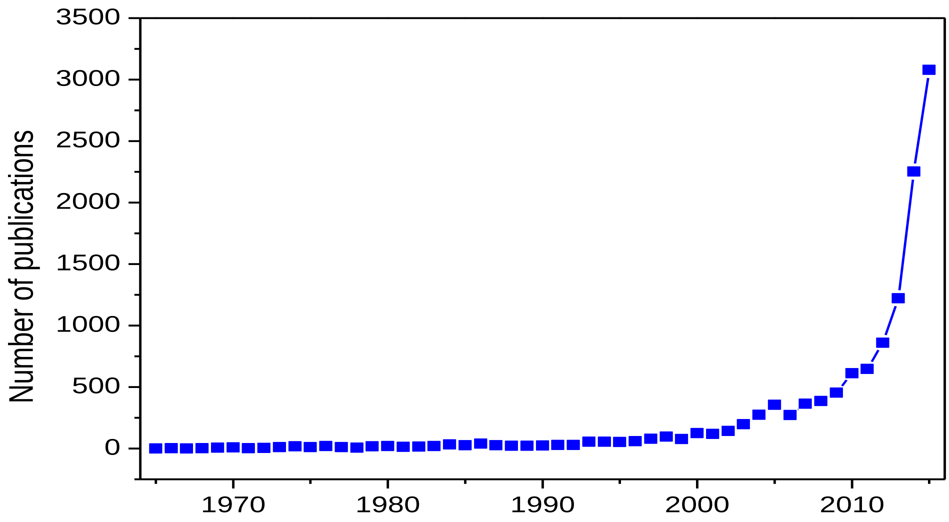


Figure 3-5: Total number of AM publications globally per year

3.2.2. What are the top countries that works on additive manufacturing?

As discussed before, AM is on the rise. There are many different countries that are currently, or starting to, focus on AM related research. Due to the limited public domain information from the national funding bodies, benchmarking could only be taken using Scopus to analysis the number of total publication at an individual country level. A detailed methodology can be found in Appendix 9.1. To be noted, this analysis does not take into account of the impact factor of publications. From 2014 to 2016, **there are about 80 countries that have shown considerable interest in AM**, with more than 10 publication. Among these, the top 20 countries are summarised in Figure 3-7 and the champion authors listed in Figure 3-7. **The leading four countries consist of US, China, Germany, UK with highest amount of publication from 2014 to 2016** (Figure 3-7)**, which is consistent with the top geographic market in Section 3.1.4.**

Since the 1980s, **the EU has started to fund AM research, with more than €160 million funding between 2007 and 2013** [1]. This is mainly under the EU FP7 program up until 2013, after which it was replaced by the Horizon 2020 program. Several of the AM research projects funded through the previous FP7 platform are due to complete in mid-2016 [1]. A few example projects include;

- The €4.3 million RepAIR project that aims to make future repair and maintenance in the aerospace industry more efficient and cost effective using AM technologies. They have demonstrated a "high batch repair solution" using SLM technology [13].
- The European Space Agency funded, €0.5 million project at Trinity College Dublin to develop a 3D printer for space missions [14].
- The €4.2 million NANOMASTER project which aimed to developed the next general multi-functional, graphene-reinforced nano-intermediates to be used in existing production process [15].

The UK was the leading EU country in terms of engagement in EU research activity, exceeding all other EU countries, including Germany that has the second largest percentage of AM machine vendors in the world. Based on the 2012 SIG report [16], 45% of the current FP7 AM focused projects were led by UK institutions. In addition, the UK used to be the second largest source of conference papers [16]. However by looking into the recent publication data, **the UK is ranked at 4th with close match to Germany, as China is climbing to the top 2 countries. The US maintained its 1st place in AM related publication.** The affiliated countries of leading authors includes the top 4 countries, such as US, UK and Germany, and some important players, such as Australia and Singapore Figure 3-7.

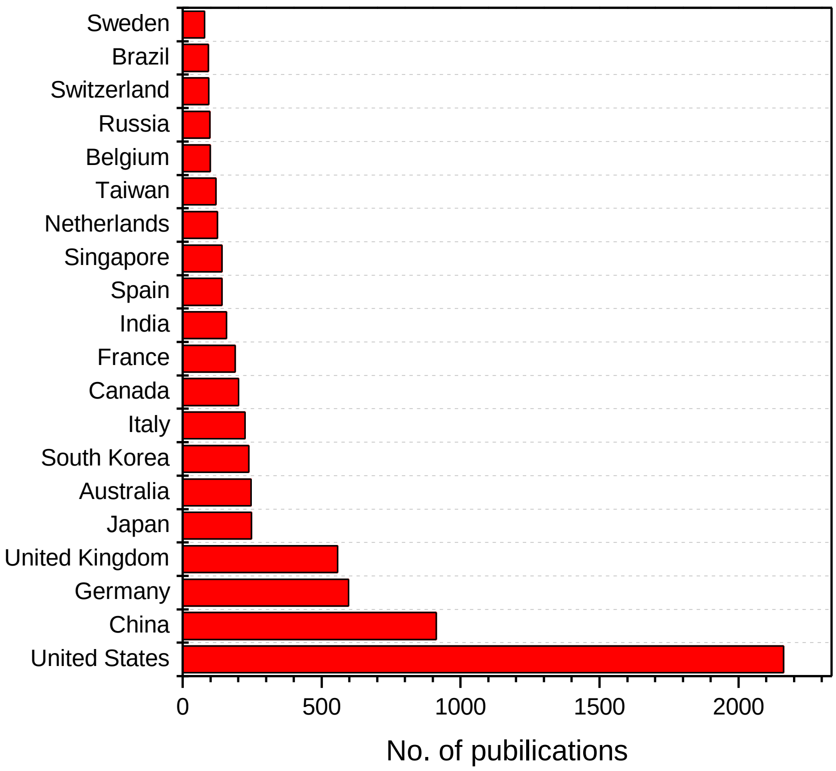


Figure 3-6: The top 20 countries that work on AM research

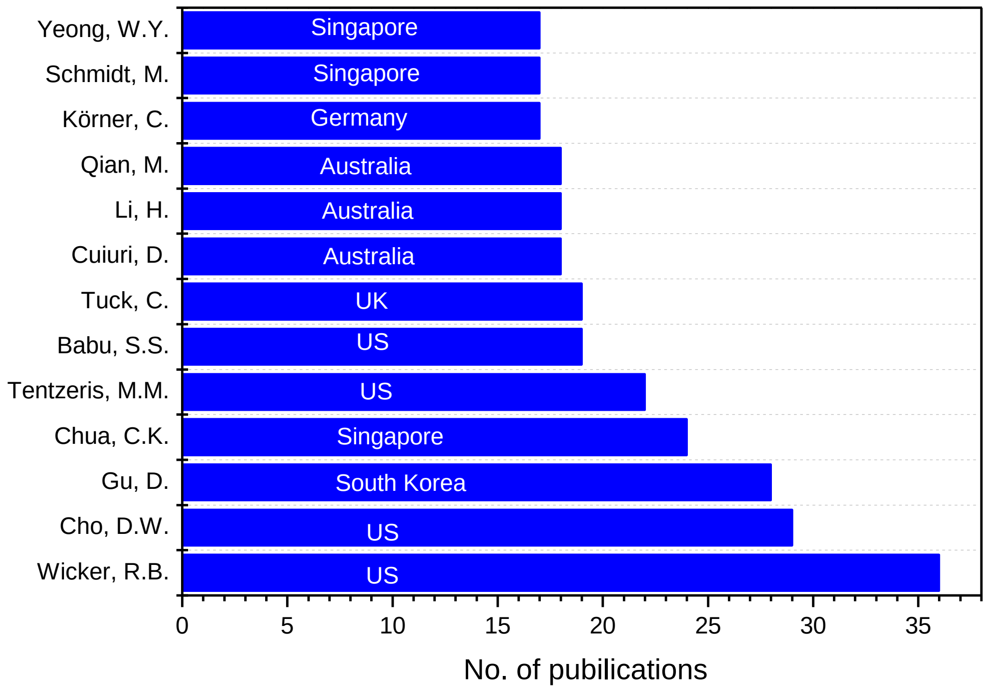


Figure 3-7: The top 13 authors in AM research

Currently, there is no publicity available examples of large scale[16]**, routine production using AM technology yet, but some countries are acting quickly to address this.** In 2014, Oak Ridge National Laboratory (ORNL) managed by the U.S. Department of Energy introduced the Big Area Additive Manufacturing (BAAM) technology [17]. In late 2015, the New York State announced they were building a $125 million industrial-scale 3D printing plant in partnership with Norsk Titanium [18]. This is the first industrial-scale 3D printing plant in the world for making aerospace-grade metal components. It is located in New York and to be operational by the end of 2017. The plant will begin with 20 MERKE IV™ RPD™ machines to establish a baseline production level of 400 metric tons per year of aerospace-grade, structural titanium components [18]. Alongside the US, China is another country acting actively to develop large scale AM technology since 2012 [19]. There are a few Chinese organisations focus on the production of 3D printed parts in titanium alloys, super-alloy and stainless steel for aerospace, including Beihang University, North-Western Polytechnical University, Hangzhou University of Science and Technology, Dalian University and Nanfang Ventilator Company. However, large scale AM printing technology have yet to be fully addressed by UK research, this missing link could potentially present as a new opportunity to UK organisations. The only project of note is the wire and arc additive manufacturing (WAAM) process at Cranfield University [20].

3.2.3. Who are the top organisations worldwide that work on additive manufacturing?

The top 20 organisations internationally are listed in Figure 3-8. It can be seen that the top organisations correlates quite well with the top countries given in Figure 3.8. In the top 20 list, there are 7 organisation from the US, 4 from China, 3 from the UK, 2 from Germany, 2 from Australia, 1 from Singapore and 1 from Belgium. It should be noted that geographical data can skew conclusions based on centres of excellence. For example, a geographical perspective Singapore is relatively low on the ranking, but from the institutional data, Nanyang

Technological University is the highest ranking university in terms of number of publications. **The University of Sheffield, University of Nottingham and Loughborough University from UK are identified here as key players in AM research globally.**

Global networking is mainly achieved by international conferences. The International Conference on AM & 3D Printing [21] is now established as one of the world's leading knowledge transfer and networking events focused solely on the production of end-use components using additive 'layer-based' technologies [22]. The conference includes both invited academic and industrial speakers from around the world, discussing topics such as AM process and materials development, business & retail strategy for AM products, supply chain management and process modelling developments. The event is regularly attended by approximately 300 delegates from around the world, representing some of the world's most innovative companies and brands. The Eleventh International Conference was held by the Additive Manufacturing & 3D Printing Research Group (3DPRG) based at the University of Nottingham, in conjunction with Added Scientific, during July 2016 in Nottingham [21].

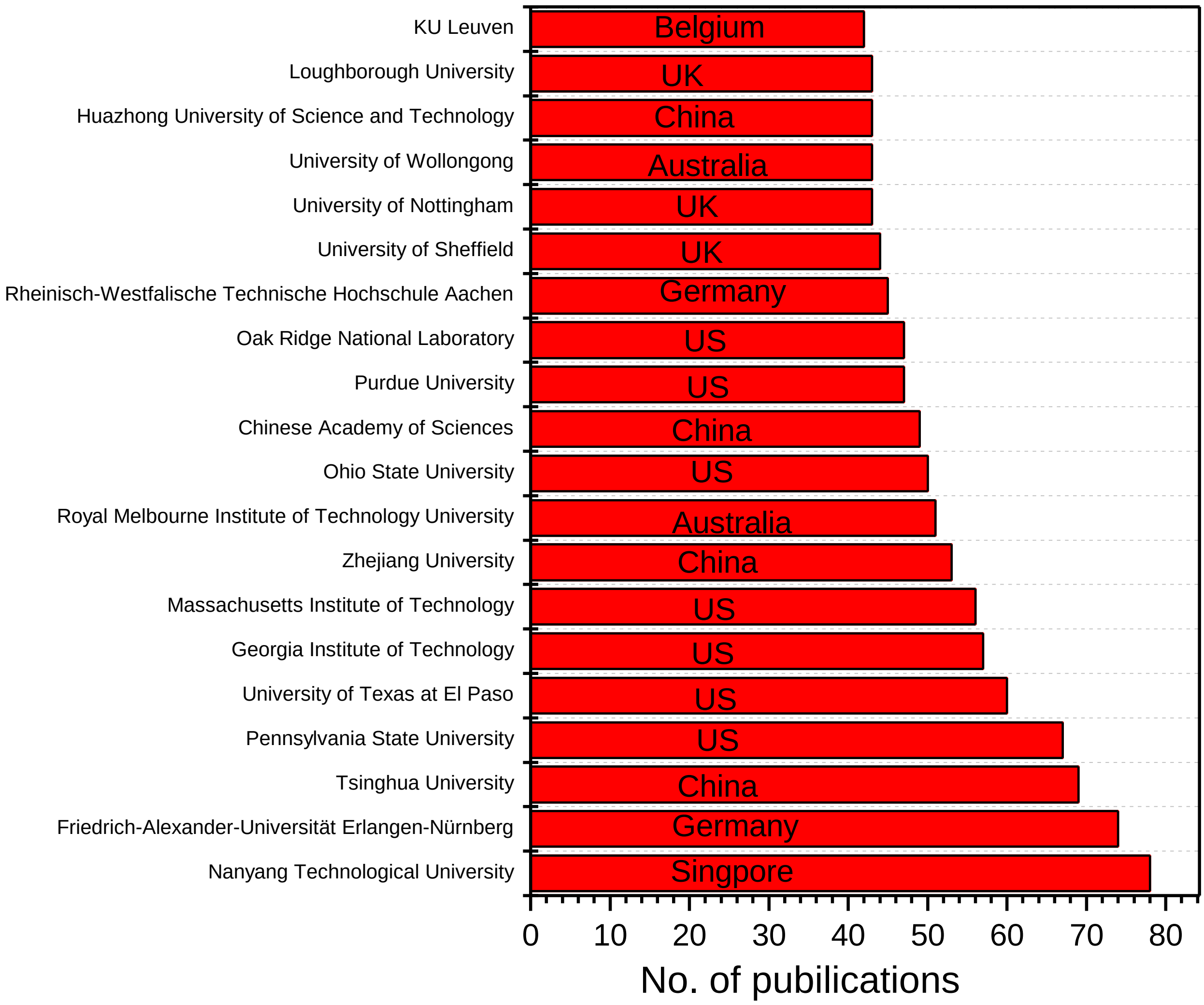


Figure 3-8: The top 20 organisations that work on AM research internationally

3.2.4. What is the global research focus on additive manufacturing technology?

The mostly widely studied AM technologies are identified as: SLM, FDM, SLA, SLS, and EBM, with the number of publications shown in Figure 3-9. Figure 3-10 then shows the distribution of publications from only the top 10 countries in each area. Unsurprisingly, the US has published the heaviest in these areas, especially with over 40% of publication in FDM and SLA. The rest of the contributions are mostly from the other 3 top countries, including the UK, Germany, and China. Specifically, the UK's involvement ranged from 6% (EBM) to 13% (SLS). To be noted, High Speed Sintering (HSS), a type of SLS technology has been heavily influenced by UK contributions. It is a combination of powder bed fusion and binder jetting that was initially developed at Loughborough University and then later adopted by Sheffield University [23]. Applications are being developed with funding from the UK government and industrial partners. Prof. Neil Hopkinson, the original inventor, set up an inkjet technology company called Xaar, with the goal of accelerating the commercialisation of HSS. The potential of HSS could be a unique strength to the UK.

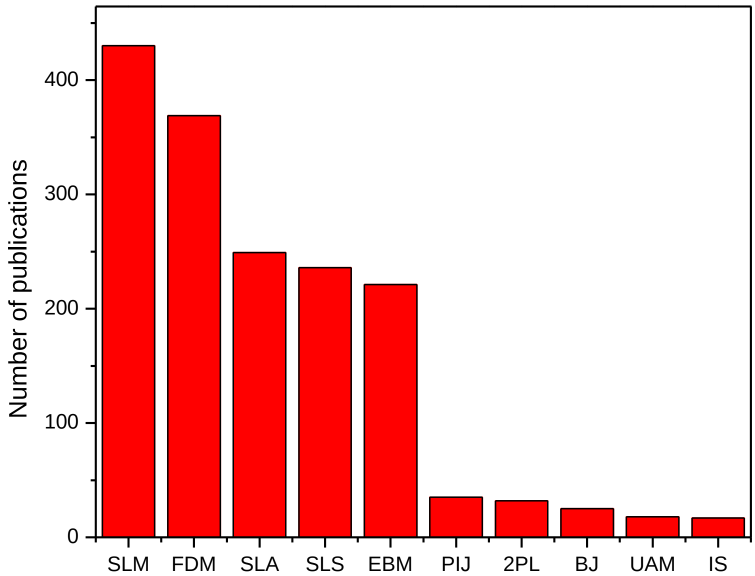


Figure 3-9: The total number of publications worldwide of various AM techniques

There are also some research publications focused on Polymer Ink Jetting (PIJ), Two Photon Lithography (2PL), Binder Jetting (BJ), Ultrasonic AM (UAM) and Infrared Sintering (IS). UK is predominantly strong in these AM techniques, especially with over 27% contribution to publication in PIJ as seen in Figure 3-11.

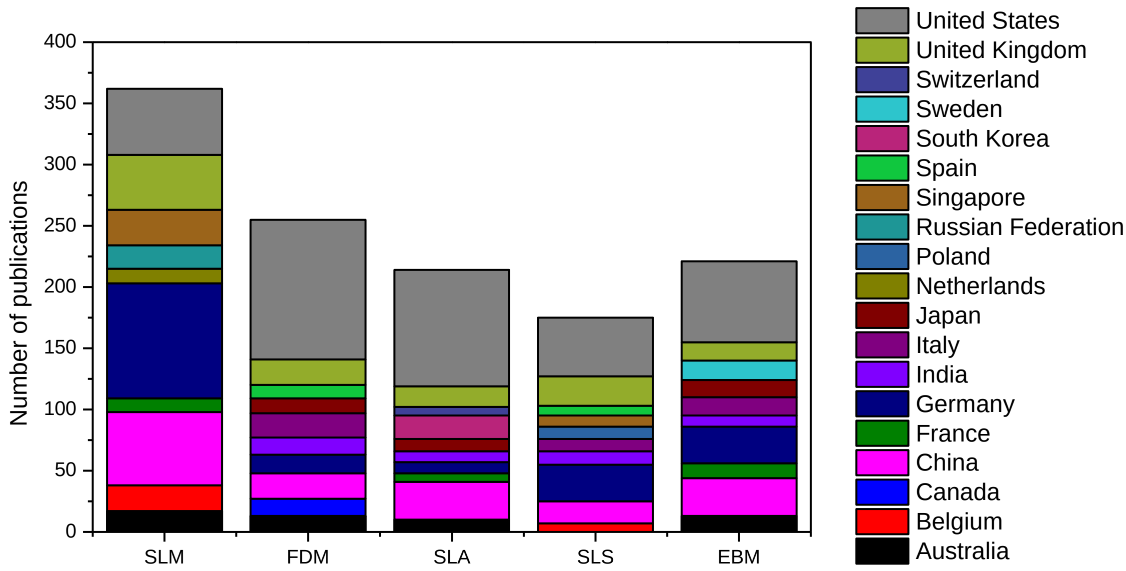


Figure 3-10: Number of publications the top 10 countries in each field

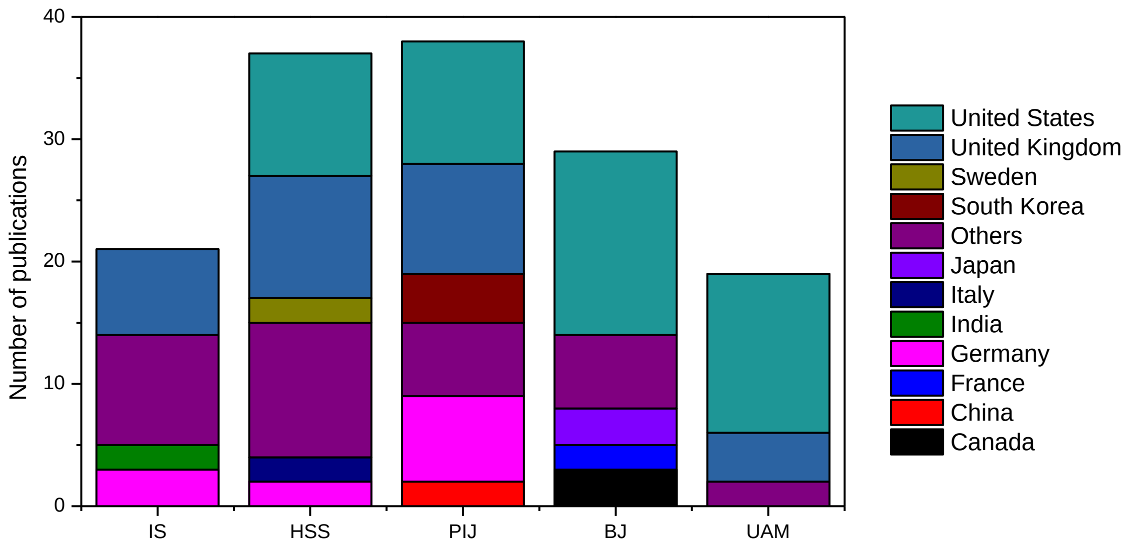


Figure 3-11: Number of publications by different countries divided into niche AM technologies

3.3 Conclusions

Global market trends

- In 2015, the AM global market was worth $5.9 billion with industrial applications making up 93% of this vs 7% from the consumer market. This is forecasted to grow to $21 billion by 2020, representing a CAGR of 29%.

- Whilst the value of AM is mostly from industrial applications this still only represents 0.02% of global manufacturing value, suggesting that growth in industrial areas will continue at pace.
- Automotive, aerospace, medical and consumer products are industries which have the highest global markets.

Global Research trends

- Along with sustained double digit growth in global AM market, global AM research is anticipated to grow continuously in the next 10 years with increasing number of publications, which also indicates healthy amount of funding have been committed globally.
- Global networking is mainly achieved by international conference with limited international strategic direction and collaboration.
- The leading countries consist of the US, China, Germany, UK, which is consistence with the top geographic market.

Mapping UK's AM research internationally

- The EU has funded AM research for a number of years, with more than €160 million. This funding identified the UK as a leading EU country in terms of engagement in EU research activity, exceeding all other EU companies before 2013, but now it is competing with Germany.
- It is clear that the UK holds a prominent global position in the global AM research community and is engaged in the development of both AM technology and applications, but far from leading in any one specific area.
- The UK has shown considerable contribution to different AM technologies and lead in the development of relatively immature techniques, such as PIJ, IS, HSS and UAM. This potentially will lead to the development of advanced or new commercialised AM techniques.
- The UK is not yet considered as a leading industrial AM machine source, when compared to Germany with 6 vendors or the US with 10. However, the UK does have the potential building blocks to become one, with Renishaw being one of the few UK based market leaders. Potential processes such as HSS and SLS offer opportunities for new UK vendors to emerge.
- There are three UK universities identified as top 20 organisations internationally, including university of Sheffield, University of Nottingham, Loughborough University.

4. Mapping additive manufacturing research activities nationally in UK

The results from last chapter are positive, demonstrating a high growth in both global markets and research activities, but along with threats and opportunities. To maintain or stimulate the strength of the UK's AM research globally, the key is to review the recent UK publically funded research activities that have been undertaken. This is done in order to identify the capability and changes in the UK's AM research, the current or merging gaps in the research base nationally.

4.1. What is the overall additive manufacturing research trend nationally?

It is evident that the UK's research publication followed similar trend as the global research, with substantial growth from 2000 to 2015, reaching a peak of 215 publications in 2015, indicating a lot more AM research activities was taken place in the UK's research base. It is forecasted to see the growth continued in 2016. The data in this section is gathered using Scopus as a search tool and more details can be found in the Appendix 9.2.

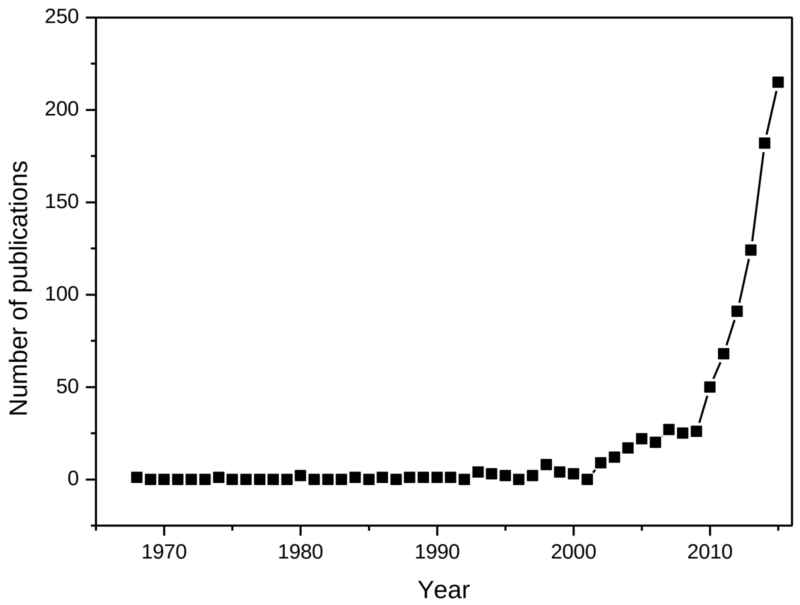


Figure 4-1: Number of AM publications in the UK

4.2. How much total funding is allocated for additive manufacturing research in the UK?

The UK government and associated industries are committed to driving AM forward in the UK, as the total amount of AM funding has increased from £15 million in 2012 to almost £40 million estimated in 2015 in Figure 4-2. Figure 4-2 is the summary of projected funding on AM research in the UK, based on three literature sources, including the 2012 SIG report [16], 2015 Innovate UK report [24] and additional RCUK research that followed similar selection criteria. To be noted, overlap of projects might occur due to limited publicly available information. More details on the methodology is accessible in the Appendix 9.2. In addition, a total of £52 million of funding has already been allocated to projects taking place in 2016

(Figure 4-2). There was a small incline in funding in 2012 and 2013 observed, mainly due to the end of two key funding initiatives, such as the ERDF (European regional development fund) and RDA (regional development agency) [24]. This has now been offset by higher investments from Innovate UK and EPSRC [24]. This may result in a higher estimated value for total funding. It is evident in Figure 4-2 that **the amount of funding will continue to grow over the next few years, as driven by the significant expansion in global AM market and government policy** [4,12,25,26]. In a recent published Technology Strategy Board study named "A landscape for the future of high value manufacturing" [1], AM has been identified as one of 22 priority technologies which should be developed as a UK national competency to meet future challenges, and enable business to respond to changing global trend and new market drivers. Following this call, Innovate UK recently opened a competition in May 2016, called "Connected Digital Additive Manufacture" with a total fund of £4.5 million [27]. This is **the first big UK specific funding call for AM research** [27]**.** The call's objective is to help companies adopt advance AM technologies, in order to overcome barriers to business growth in AM. The next Innovate UK call for AM specific research will be conducted under round 2 of the 'Manufacturing and Materials' call, in November 2016. This call has about a £15m funding pool, and is planned to be repeated annually.

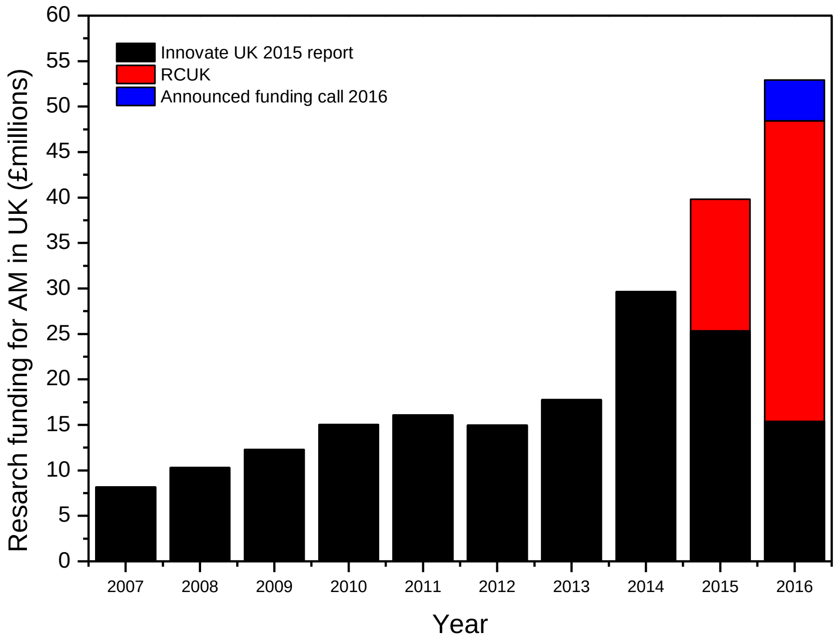


Figure 4-2: Research funding on AM in the UK (2007-2015 from [24], 2016 from Table 9-4 in Appendix 9.2).

By looking into the funded AM projects collected in 2015 and 2016 via Scopus, it is possible to capture the recent changes in research topics. As shown in Figure 4-3, **55% of funding in 2015 and 2016 was attributed to the development of general materials, processes and application, such as improving EBM and HSS systems, and material development for titanium powders**.

Research on 3D printed electronics have played an important role, which used to be identified as one of the missing links in AM supply chain, now it is been heavily addressed in 2015 and 2016. There is considerable amount of funding, 29%, is for research on 3D print electronics, targeting to develop suitable material/process/design for mainly embedded sensors, electronic signal routing, optical fibre fabrication, and integrated energy storage devices [12]. To structurally integrate electronics in finished parts, many researcher have explored **combining AM and Direct Write (DW) technologies which enable the selective deposition and patterning of materials**. DW process have been successfully hybridised into SLA, FDM, UAM and PBF, to enable the formulation of complex and conformal electronics [28–34]. Specific application examples includes 3D antennae, conformal or discrete electronics, magnetic sensor, force sensor, signal routing and batteries [12]. However, the current design software is not yet optimised **to support the modelling and analysis of these heterogeneous and multifunctional assemblies, thus this remained significant need addressed for design software.**

Research on AM applications in biomedical applications have stood out from other applications that with large number of relatively medium to small sized projects, adding up to about 9% of total funding in 2015.

AM is now pushing the frontier of new breeds of design approaches and tools, including explorations on topology and geometry design, material design, computational tools and interfaces development, manufacturing tools and process development. However, current research on design has shown to be the least funded area, with limited development in some of these areas. One of the instances of funded design related projects is “Design for AM”, a EPSRC grant is awarded to Prof. Richard Bibb from Loughborough University and Dr James Moultrie from University of Cambridge that officially launched in 2016, to develop design rules and guidelines specifically for AM of end use products and components.

There are also additional areas, such as IP issues, quality of materials and recyclability, education issues, manufacturing standardisation, of which very limited resource have been allocated. Thus, there is an emerging need to cope with the fast development in AM technology.

Similar trends have been followed in 2016 with a 2.4 fold increase in funding. Funding for general material/process/application has increased to 77%, **mainly due to a few large grants is assigned to aerospace applications**. The AM funding focused on aerospace and biomedical application in 2015 and 2016, as these two areas have been identified as the top application market for AM in Chapter 3. In addition, **the industrial funding is predominately driving projects with low-mid TRL** as described in 2015 Innovate UK report [24], which is even lower TRL than in the 2012 SIG study [16]**.** This may be explained by companies having realised that current rapid prototyping platforms are not equipped for industrial manufacturing applications, thus **fundamental changes must be met at a core-technology level to drive future adoption, implying great need for more advanced or new AM process for large scale and speedy production.**

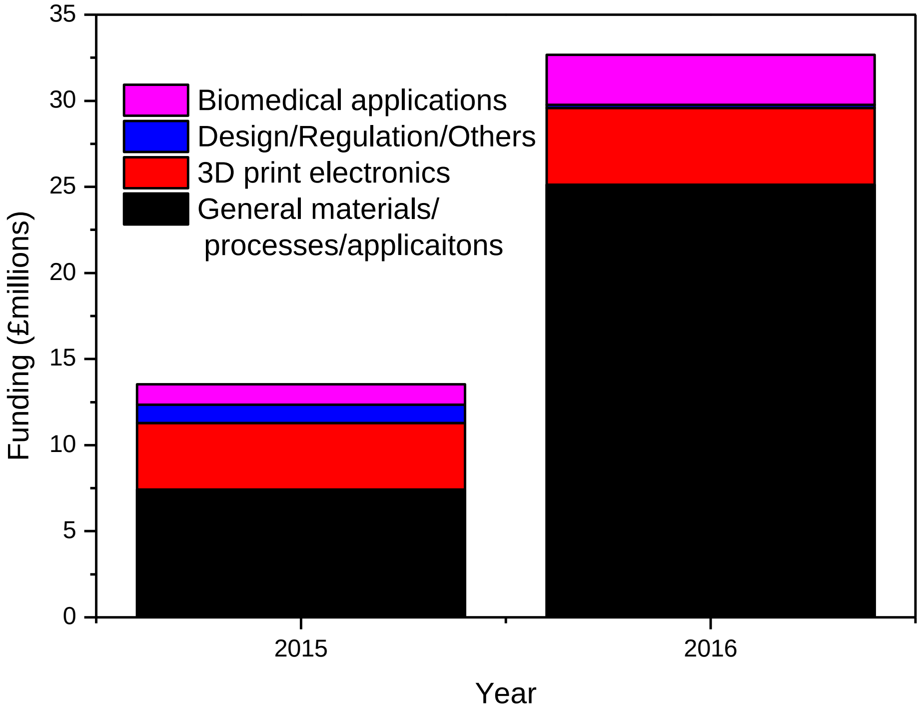


Figure 4-3: Active AM projects funded in 2015 and 2016 in the UK (via RCUK searches)

4.3. Who are the leading organisations that work on additive manufacturing in the UK?

A total number of 245 organisations have been recognised as a named partners within AM research projects in the UK in 2015 Innovate UK report [24]. Some key organisation that received sizeable funding are listed in Figure 4-4. Here, **a long tail distribution is clearly found, with very small number of organisations receiving a high proportion of funding**. The average amount of funding per organisation since 2012 is about £289,188. The universities of Nottingham, Sheffield and Loughborough have received 38% of the total funding. Among them, University of Nottingham is leading the way by receiving £30 million in total since 2012, along with highest number of projects involved. The University of Cambridge and Imperial College London contributed to a very small proportion which were included in the "all others combined" category since 2012, but these two are growing very quickly in 2015 and 2016 and will be discussed more in later section.

A few of industrial organisations have also played a key role in AM research, such as The Welding Industry (TWI), Centre for Defence Enterprise, Manufacturing Technology Centre (MTC) and Renishaw. In February 2015, the UK AM National Strategy launch event at MTC sought to maximise business growth and long-term economic value through successful industrialisation of AM [35]. Following on in June 2015, the national centre for Net Shape and AM was formally launched at the MTC. This aims to use two complementary techniques to demonstrate low and high volume production of complex parts over a wide range of sizes. MTC will receive a total of £2 billion over the next seven years from UK government and industry. The MTC have shown significant interest on multifunctional lattice structure, material and software capability for Polyjet systems, post process and hybrid structures [36].

There are very few UK based print vendors, the largest and most notable is Renishaw, who specialise in metallic SLM processes. Renishaw have set-up worldwide application centres in US, Italy, China and Germany along with a global resource centre aiming to share AM knowledge more efficiently [37]. Renishaw launched an AM 500 machine in late 2015, a new production-focused PBF machine. The AM 500 machine was designed specifically for shop-floor production of metal parts and features automated powder and waste handling systems. It will also launch a new Quantum software that could enable automated generation of support structure with easier software operation [37]. **Currently, there are limited new emerging machine vendors. However there has been substantial activity in developing new technology platforms, such as metal jetting processes, which are still far from commercialisation** [24]**.** For example, Hybrid Manufacturing Technologies was founded in 2012 by Dr. Jason Jones and Peter Coates as a spin-off from a collaborative research and development project, employing additive and subtractive manufacturing together, with the goal of creating a superior finished piece [38]. In addition, The PWC Innovations Survey found that 25% of manufacturers plan to adopt AM in the future in some ways [39].

As driven by AM technology development and greater global demand for AM, more and more big companies are gearing up to offer AM machines, materials and services, such as GE, Lockheed Martin, HP. Some OEMs are competing to introduce or have introduced new AM systems, including HP, Canon, Michelin, Ricoh, Toshiba, Lenovo and Polaroid [4,25]. For instance in 2016, HP launched its Multi Jet Fusion 3D printer, an inkjet printer, which target at rapid prototyping [40]. Lockheed Martin has developed a big Sciaky 3D printer with electron beam additive manufacturing (EBAM) technology to build high quality parts for aerospace along with a Multi-robotic clusters for simultaneous AM [41]. Canon 3D, a world leader in imaging solutions, is a relatively new company in the area of AM [42]. Canon have announced a new strategic partnership with Materialise and is getting ready to enter the 3D market [42]. These OEMS have greater distribution capabilities and global reach will certainly accelerate the worldwide development of the AM network.

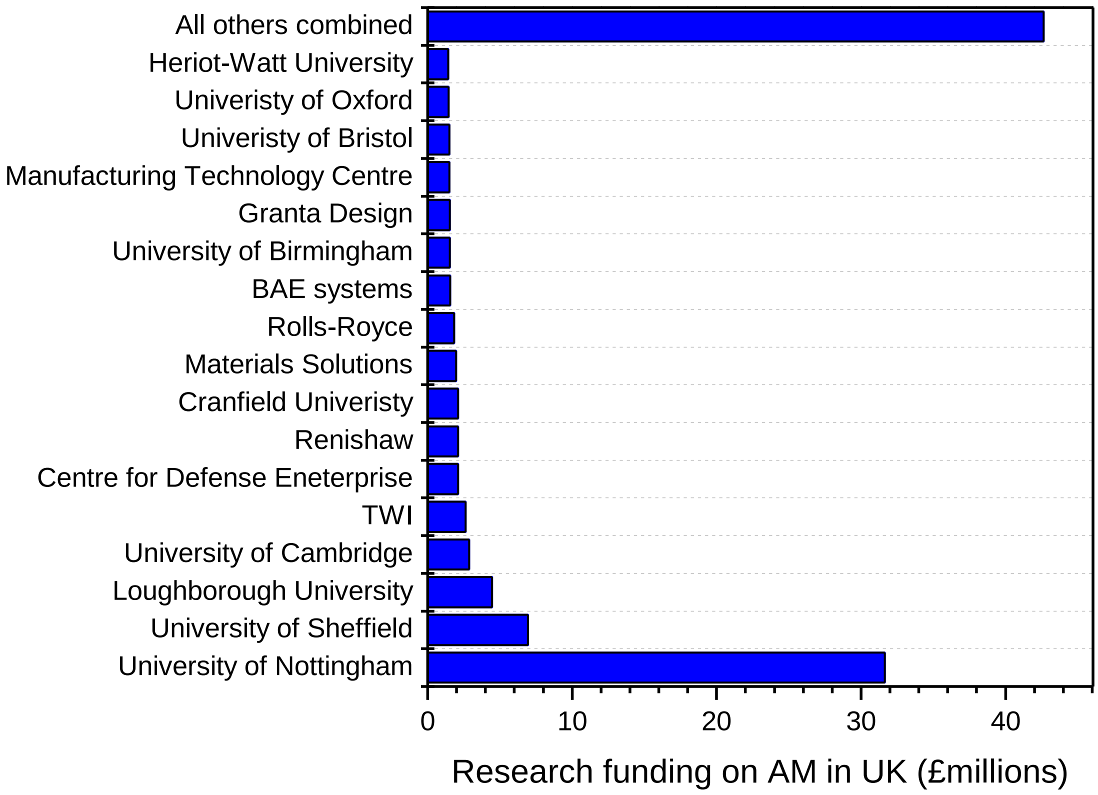


Figure 4-4 Research funding received in UK organisations [24]

4.4. What is the geographic distribution of academic research?

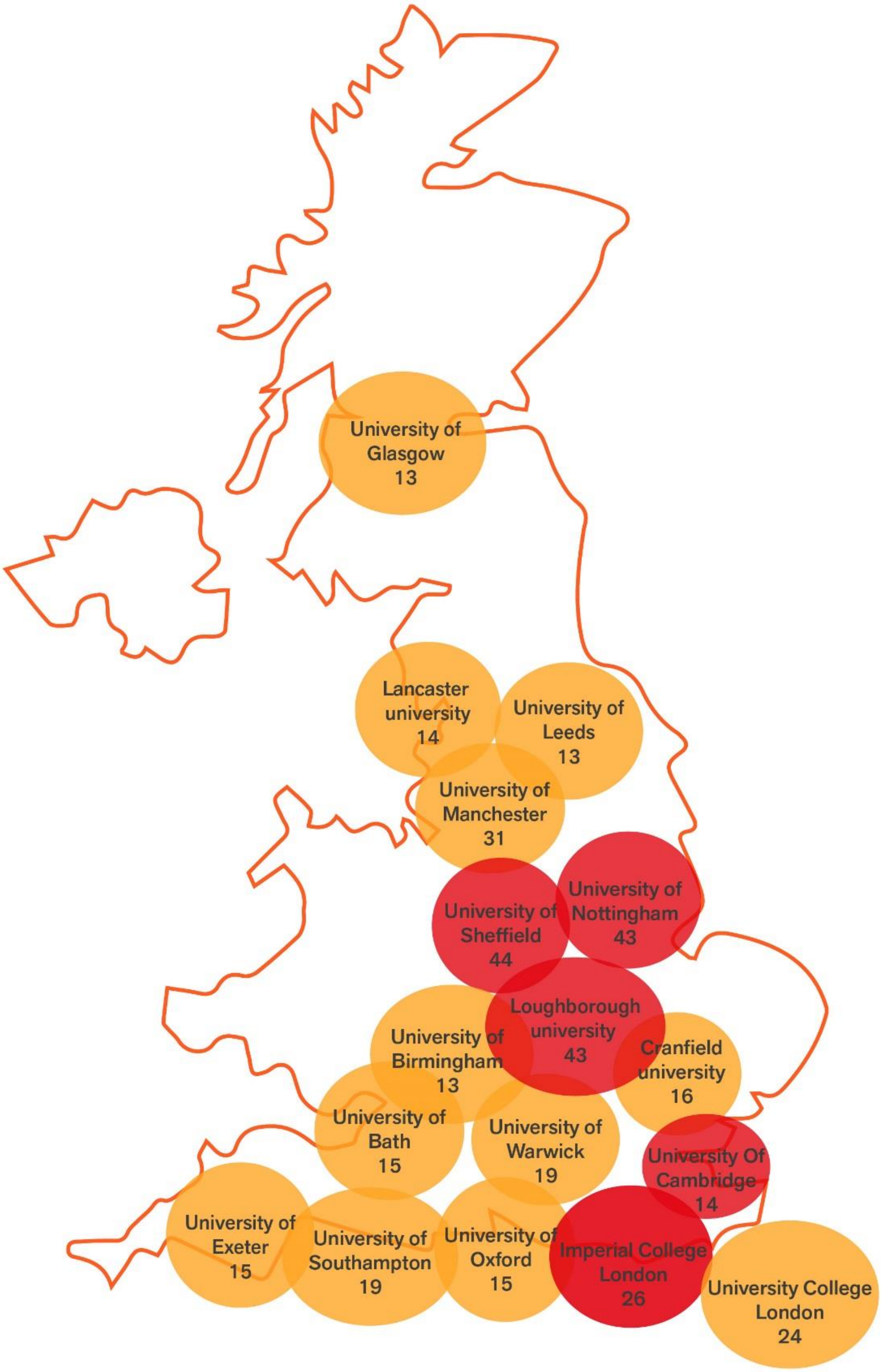


Figure 4-5: Geographic distribution of key universities that work on AM research based on the amount of publications in 2014-2016 via Scopus. 5 coloured universities have been selected for in-depth analysis.

There are about 41 UK universities identified in 2015 Innovate UK report [24], which are involved in AM research, increasing significantly from 24 universities in 2012 [16]. Based on their publications from 2014 to 2016, some key universities are shown geographically in Figure 4-5. **The universities within the east midland and south Yorkshire are the most active in AM research with the majority of publications**, this includes the universities of Sheffield, Loughborough and Nottingham, each with over 40 publications that received the most significant sum of funding. The data on publication is collected using Scopus with the detailed methodology found in the Appendix 9-2. One reason for this is that Professor Phill Dickens who initiated research activities on AM in the mid-1990's has his legacy work linked to academics that are now working at Loughborough, Sheffield, Nottingham and Birmingham, along with staff within TWI and MTC [24]. **This trend has been observed since early 2000, but now we can see more contribution emerging around from the University of Cambridge, Imperial College London, University College London, and a few universities dotted in South West**. In the north, only the University of Glasgow has shown considerable activity on AM research. Therefore, 3 historically strong UK universities including universities of Sheffield, Loughborough and Nottingham, along with the 2 fastest growing universities, such as Imperial College London and University of Cambridge, were selected for detailed analysis in later subject.

The key authors shown in Figure 4-7 are mostly aligned with top identified organisations, mostly from the university of Nottingham and Sheffield. However, authors from other 3 selected universities are not identified here, possibly due to their publications being more scattered between numerous different authors.

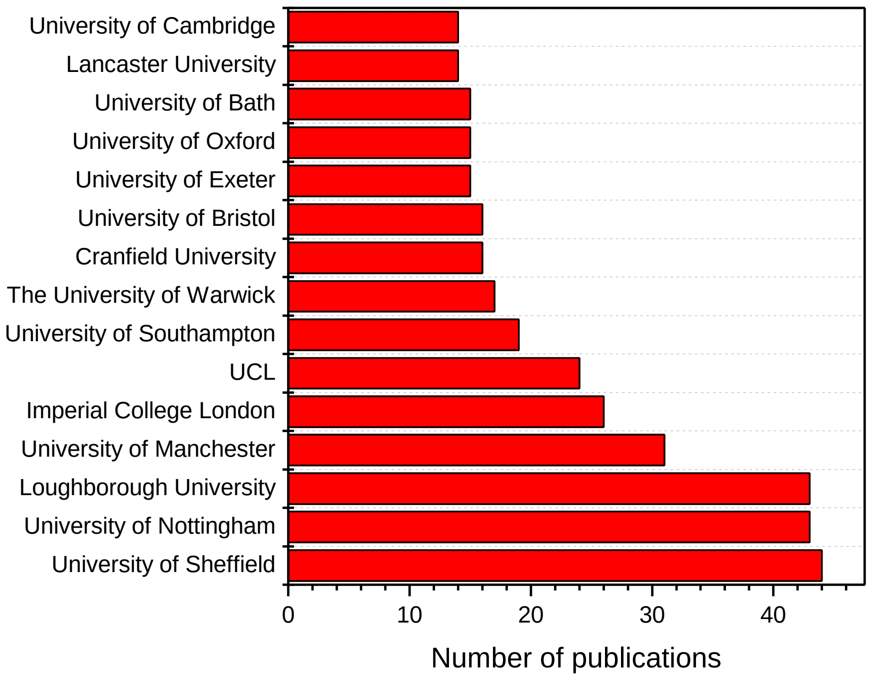


Figure 4-6: Top 15 UK universities on AM research based on number of publications from 2014-2016 via Scopus

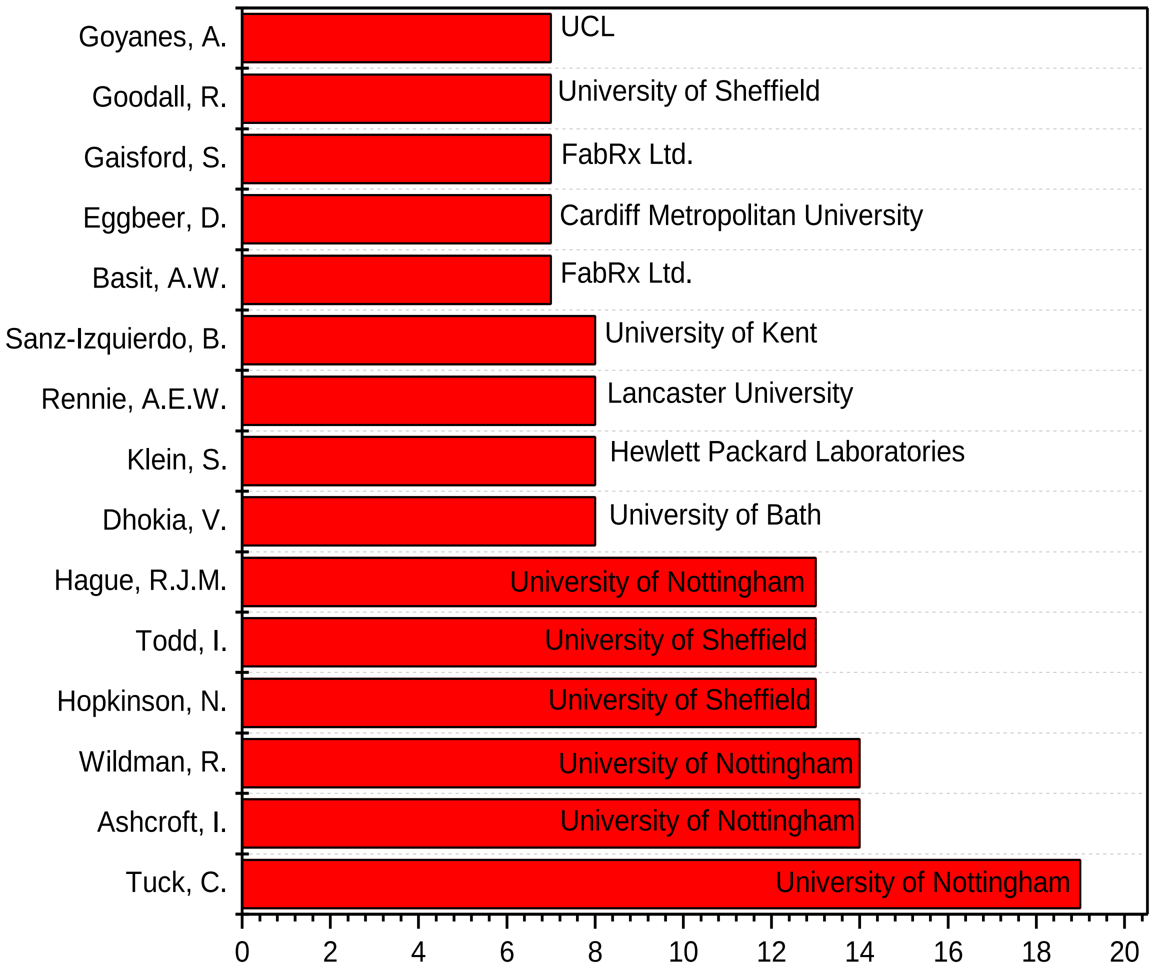


Figure 4-7: Number of AM publications by UK based authors via Scopus (2014-2016)

Another alternative to assess the funding received by organisations is to look at the number of projects that each organisation is involved with and the number of partners that they collaborated with. It is shown that **the UK has a well-established and equipped AM research community**. The average engagement for industry and university is about 10 and 11 years. It is found that industrial companies, such as Renishaw and BAE systems, who are part of an extensive research network, are heavily involved in both metrics, along with the top 3 UK universities and research organisations (e.g. MTC and TWI).

However, there are limited formal networks between these organisations beyond the links created by individual projects, reflecting a fragmented UK research landscape. In addition, there is no formal requirement to share good practice or learning between the different projects groupings. This could raise concerns about the strategic direction of the UK research community and the cohesion between the members. **This issue have been recognised and have started to be address by the UK government since late 2015** [24]**,** by introducing EPSRC fellowships to support researchers in underpinning future manufacturing technology, such as AM. For instance, Prof. Phill Dickens from the University of Nottingham is funded to work on “The future of AM” [44]. This is aiming to not only encourage UK academics from various disciplinary, such as physics, chemistry and materials, to originate ground-breaking new AM process with higher building speed and volume, but also to establish a UK national strategy on AM to accelerate the momentum of research. Another fellowship also received by University of Nottingham is for Prof. Jonathan Aylott [45], focusing on “analytical technologies in continuous and AM” in pharmaceutical industry. There are also organisations that were set up to bridge the gap between academics, industry and government, such as MTC which was set up by the government (mentioned in Chapter 3). MTC is part of the High Value Manufacturing (HVM) Catapult network of seven research and innovation centres created in 2011 [46], with founding members from University of Birmingham, Loughborough University, University of Nottingham and TWI. The Additive Manufacturing Network (AMN) is another organisation that formed in ICL in 2016, which shared similar vision, directing to coordinates research activities strategically.

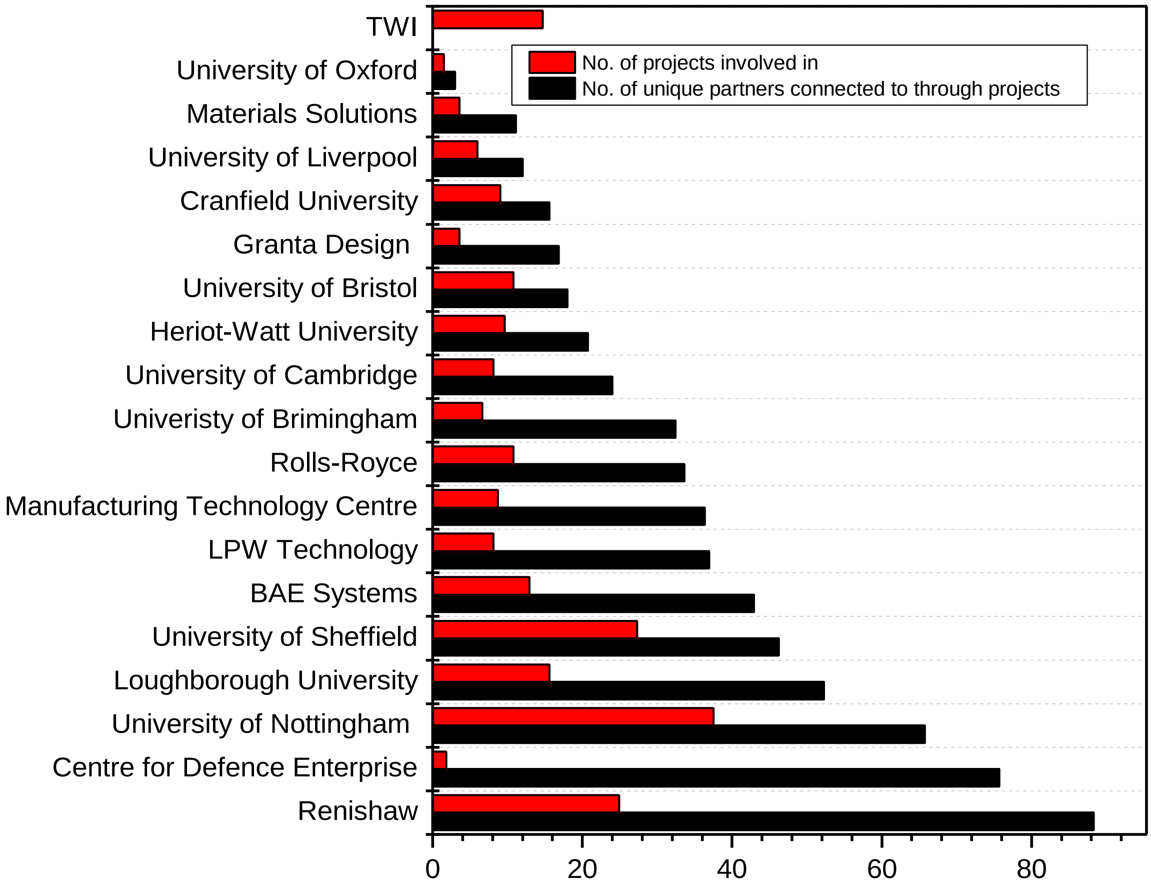


Figure 4-8 involvement of organisations in AM research and the scale of their research network [24]

4.5. What is the technology focus within research in UK universities by funding?

The UK’s research community is involved in evaluating almost all types of AM technology with a total funding of £115 million during 2012 and 2022 as reported in 2015 Innovate UK report [24], **with emphasis on PBF, DED and MBJ technique**. **Analysis suggests significantly more activity is taking place in metallic AM technology than polymer based**. It is worth mentioning that the bias towards metal reduced since 2012, with 80% of all projects focused on metallic tech, and now discrete metallic projects only takes up 66% excluding “mixed material projects”. The current research funding for metallic AM technique added up to **almost £40 million, which are still 4 times more than polymeric processes.** It is mainly due to the cost and complexity of validating materials and process into the high adoption sector, such as aerospace. **It is expected to see this trend continue in 2016 and the future.**

In terms of funding source, about **50% of funding has been sponsored by EPSRC and industrial organisations**. The rest of contribution are mainly from FP7, Innovate UK, University and DSTL. It is shown that **the UK's AM research received an appreciable amount of support from the EU, with about 18%.** This might change after 2016 as UK's decision on exiting EU, possibly leading to slower growth in AM funding, unless a greater support from the UK's organisations is provided to sustain the development in AM research.

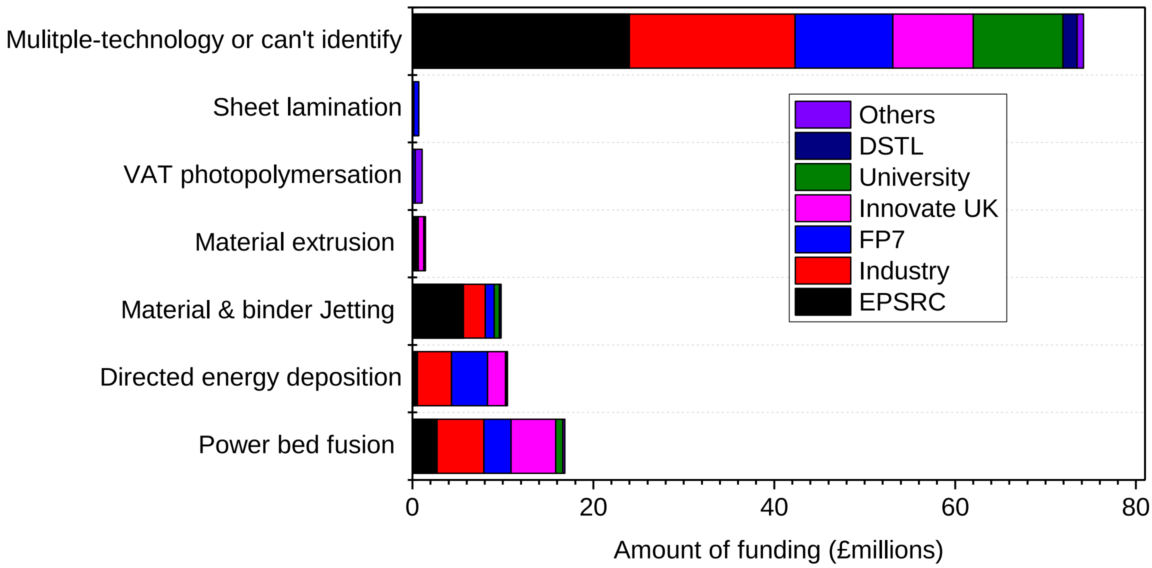


Figure 4-9: Total funding per technology type in the UK [24]

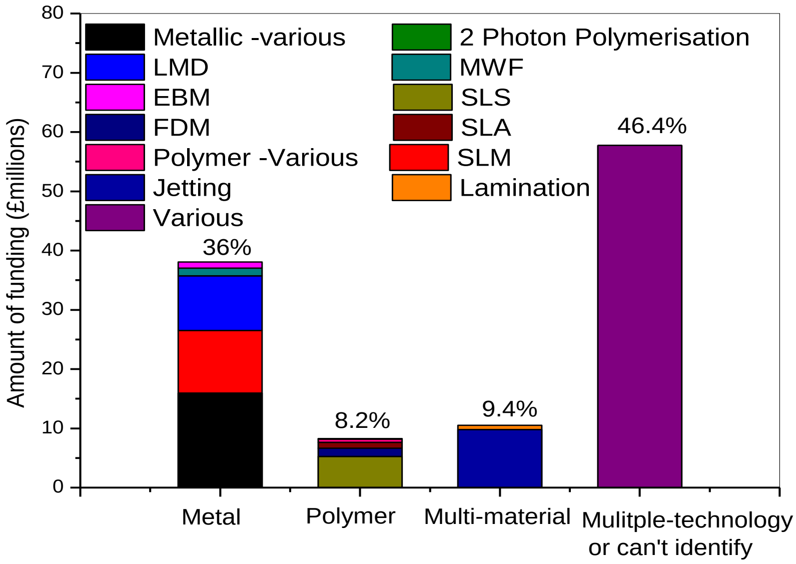


Figure 4-10: Total funding per material type in the UK [24]

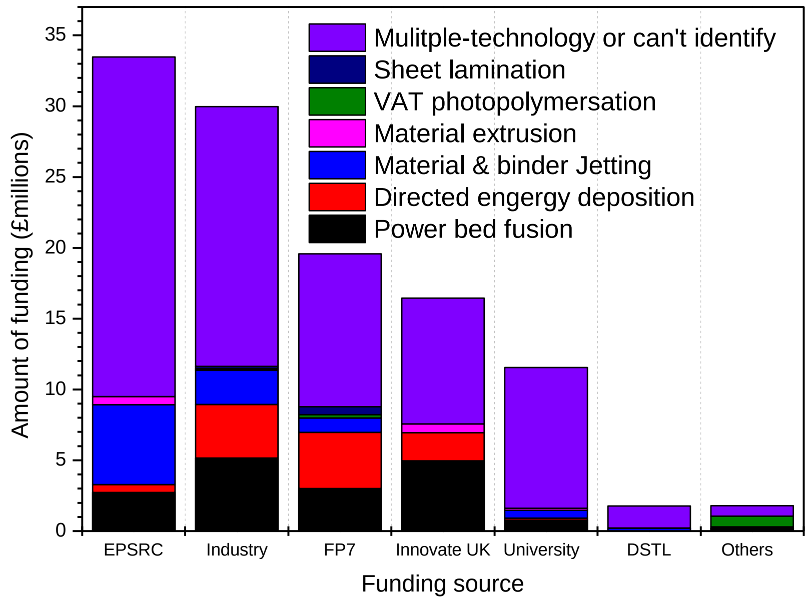


Figure 4-11: The total amount of funding per funding source [24]

4.6. Conclusions

In this chapter, the UK's research landscape has been analysed. With considerations from both Chapter 3 and Chapter 4, the strengths, weakness, opportunities and threats are summarised for the UK's AM research, internationally and nationally:

Strengths

- The UK's research publication record followed a similar trend as the global AM research, with continued substantial growth projected in the future.
- There is a well-established and broad AM user and research community in the UK, with a total number of 245 organisation involved that includes 41 UK universities.
- The universities within the midlands are the most active in AM research since early 2000, such as the University of Nottingham, Loughborough University, University of Sheffield and University of Manchester, but now we could see more contributions from emerging institutions such as the University of Cambridge, Imperial College London, University College London, and a few universities dotted in South West. Thus, a broad science base is shown in UK, enabling a great platform to develop innovations for new AM technology/systems and process validation.
- The UK government and industry have demonstrated commitment to drive AM research forward in the UK. AM has been identified as one of 22 priority technologies for high value manufacturing. A total of £115 million has already been allocated to various research projects between 2012 and 2022.
- Funding for AM research is likely to increase further over the next five years as the allocated funding in 2016 is 2.4 fold higher than in 2015.
- The first AM specific large UK funding call was announced in 2016, named "Connected Digital Additive Manufacture" with £4.5 million funding committed from Innovate UK.
- There is over 90% of total funding in 2015 and 2016 allocated to develop general materials, processes and applications related AM research. Within this, there is an emphasis on advancing general AM technology, such as EBM and HSS, and in

aerospace and biomedical applications, which are in line with the top application markets.

- 3D printed electronics has been identified as an emerging research area, and potential market sector, mainly through the successful marriage between AM and Direct Write (DW) technologies.
- Higher engagement from the supply chain with increasing funding through recent development is observed in the UK. Emerging participations from OEMs is observed, aiming to diminish AM technology barriers. However improvement is still needed from all members to achieve a robust AM supply chain through to design, simulation and modelling software tools.
- Metallic AM technologies are receiving significantly more research interest over the last few years, with almost £40 million funding received from industry and government. This will potentially provide UK a head start in metallic AM technology.
- The UK's AM research is identified to be good at high value, low volume manufacturing, along with world class design capability. With sufficient education, this should be able to drive the commercial success of AM, with vehicles such as "Maker Spaces" in the form of examples such as the Imperial College Advanced Hack Space, enabling a university-level informal learning environments.

There is potential to adopt AM widely as the UK's industry have a much better understanding of AM technologies since 5 years ago.

Weaknesses

- There is an extreme long tail effect identified, within the UK's AM research with a very small number of organisations receiving a high proportion of funding and many organisations are not linked into the main AM community.
- Despite the high growth in the number of participants, organisation are still only networking through loosely connected projects, with limited open innovation culture in the sector and little visibility of activity between sectors. Thus, limited knowledge sharing of good practice, is likely lead to some duplication.
- It is evident that a highly fragmented AM research community is found in UK. This issue has been recognised and is starting to be addressed by the UK government since late 2015, by introducing fellowship programs, such as "The future of AM" and "Analytical technologies in continuous and AM" for the University of Nottingham, along with the formation of centres of excellence (MTC) and AM research networks (AMN by ICL). It indicates that the UK government have started to take a more targeted and strategic approach, in order to maximise co-operation and network while minimise the risk of duplication.
- Low commercial exploitation of academic research is also found in the UK. There are very few UK based print vendors, the largest and most notable is Renishaw, who specialises in metallic SLM process. Efforts towards solving this have begun, with examples being the 3DP-RDM feasibility study proposal calls for redistributed manufacturing. However, there needs to be more of these focused feasibility study calls in technology areas to stimulate the increase in novel AM TRLs.
- It is also noted that there has been little commercialisation of new business models enabled by AM in the UK. There is a lack of comprehensive set of design principles, manufacturing, guidelines, and standardisation of best practice both in UK and globally.

Opportunities

- The UK's research has been supporting and focusing on fundamental studies with low-mid TRL projects, with mostly undefined application areas, such as in the development of materials, leading to future innovations and potential explorations.
- There is increasing industrial demand for skilled engineers, designers and scientists with AM education that the UK's AM research base is capable of addressing, such as the EPSRC Centre for Doctoral Training in AM.
- There is increasing global market value for AM machines, service and material globally. Growing interest in private sector investors have emerged as sufficient media coverage publically.
- Improvement on existing AM processes are being developed continuously, along with emerging new AM technology, leading to new opportunities.
- Currently, there are limited numbers of emerging machine vendors. However there has been substantial activity in developing new technology platforms, such as jetting processes, which are still far from commercialisation. There is also increasing amount of industrial companies who are willing to get involve in AM.
- The use of AM technology can be considerably disruptive for industries. Analysis suggests that using AM technology enables companies to adopt more agile flexible business models.
- Centres for doctoral training in AM and manufacture the future funding calls could lead to high level of funded experts in the future.
- EBM research is not as popular as DMLS currently, but it has received growing interest from aerospace companies due to speed and reduced thermal stresses.
- The UK government policies are leading industries to change their traditional approaches, such as AM uptake with light-weighing to reduce emissions in vehicles. In addition, many schools in the UK have followed the recommendation of UK government's report in 2013 entitled "3D printers in schools: users in curriculum" [47], aiming to use AM techniques to support computing, design, technology, engineering, science and math.

Threats

- There is increasing global competition. The UK is losing the advantages that it had gained in some areas of research excellence with not only strong competition from the US and Germany, who are investing heavily in developments and succeeding in commercial exploration, but also with relatively new entry by other high tech countries, such as China, Russia, Singapore and South Korea.
- Oversea ownership of core IP with top patent assignees from foreign countries is found, such as Stratasys from Israel (formerly from the US), 3D systems from the US, Samsung electronics from South Korea.
- The UK's AM research is partially supported by the EU, currently about 18%. With the UK exiting the EU, this could potentially pose a threat to the growth in AM research unless the gap in funding is addressed by the UK organisations accordingly.
- Currently, there are very few innovative business models applied to the AM industry.
- Take up of AM technology is hindered by legislation around digital ownership, copyright law and liability, which is largely underdeveloped and could potentially inhibit the uptake speed of the technology.

5. Detailed analysis on selected UK Universities for additive manufacturing

In this chapter, five selected UK universities on AM research are analysed in-depth based on the investigation in Chapter 4. Including the three dominant universities of: Loughborough University (LU), University of Nottingham (UON) and University of Sheffield (UOS), and the two fastest developing University of University of Cambridge (UOC) and Imperial College London (ICL). Here, we will evaluate capability of AM research in universities based on equipment availability, research topics, and amount of funding, no. of projects and number of publications.

5.1. Available additive manufacturing equipment in the selected UK universities?

As discussed in Chapter 4, UK's national funding spread across all types of AM technique. From the summary of available AM equipment (Table 5-1), **these five selected UK universities have various interests over a variety of AM technology.** Among these, there are two type of AM techniques which are available in every university; these include SLM and FDM. The popularity of SLM is mainly due to PBF have been identified as the mostly funded technology in UK in Chapter 4. Therefore every university now is competing on SLM, as one of the key metallic AM technology to reach a technology breakthrough, which was driven by high demand in industry, such as aerospace, automotive and prototyping. On another hand, Material Extrusion is not identified in the top funded technology in Chapter 4, but it is a well-developed with most affordable price, thus it is common used in different AM research. However **it is surprising to see that Direct Energy Deposition (DED) as the second highest funded technology type, which is primarily worked on by UOS and UON. The limited number of institutions working on DED may well be due to the large physical footprint required for the technology, meaning a high barrier to entry for new researchers**. Another least possessed technology is binder jetting and it is likely that most of the funding from the material and binder jetting is spent on material jetting. In addition, some specific technique, such as SLS, PIJ, and SLA, are also popular and studied by most of the universities.

UOS have been involved in every category of AM technique, and some exclusive AM machines are established, such as EBM, IS, SMD, CBJ, SMD. Consequently, this not only provides UOS a clear advantage in terms of diversity of AM technology, but also distinctive priority in future research funding on the sole-owned machine than other universities. ICL have developed substantially in AM within the last few years, now it shows equipment capability approaching that of LU and UON. However, UON have some unique machines over others too, such as LMJ, MMJ, and MPLA. To be noted, information on equipment availability in each university is collected from publically available data, such as website and online search via Research Council RCUK and Scopus. More information on methodology is available in the Appendix 9.3.

Table 5-1: AM equipment capability in 5 selected UK universities

	PBF				MJ					BJ	ME	Vat-P		DED	SL	Variety of Equipment
	SLM/DMLS	EBM	SLS	IS	PIJ	WIJ	OIJ	LMJ	MMJ	CBJ	FDM	SLA	MPLA	SMD	UAM	
Loughborough University	✓		✓		✓	✓					✓	✓			✓	
University of Nottingham	✓				✓			✓	✓		✓	✓	✓	✓		
University of Sheffield	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓		✓	✓	
University of Cambridge	✓		✓								✓					
Imperial College London	✓		✓		✓		✓				✓	✓				

Code of technology use	Strong		Moderate		Low		Available/Published	✓

5.2. How much funding is received by selected university?

Figure 5-1 states the amount of funding received by UON, UOS, LU, UOC and ICL in three categories, including projects starting from 2012-2014, in 2015 and in 2016. As indicated in Chapter 3, the UK's funding displayed an extreme long tail distribution between universities. Before 2015, UON received about 67% of the total funding (of £47.4 million) between the 5 selected universities, then followed by 15%, 9%, 6% and 3% for UOS, UOL, UOC and ICL respectively.

Though, this distribution has changed in 2015 and 2016. UON have been identified as receiving the smallest amount of funding in 2015 and 2016 and that there is only one large AM project started in 2015 which is found publically on RCUK with £132,415 funding, which aims to accelerate the uptake of continuous and AM in the pharmaceutical industry. LU and ICL have increased dramatically by nearly 2x and 4x respectively. For example, a project called SYMETA (Synthesizing 3D Meta materials for RF, microwave and THz application) is led by LU and received £4,012,827 funding. It also brings experts from University of Exeter, UOS, Oxford University and Queen Mary, University of London together with twelve industrial partners from a range of sectors, including defence and electronics manufacture. For ICL, there are a total of 8 AM projects started in 2015 and 2016 via search on RCUK. Details on methodology can be found in the Appendix 9.3. These 8 research projects have concentrated on some popular research topics, such as development for manufacturing fluidic sensors (£308,071) [48], 3D bio-plotter for biological tissue development (£171,455) [49], advanced acrylate based hybrid materials for osteochondral regeneration (£606,488) [50], AM of advanced medical devices for cartilage regeneration (£1,057,130) [51] and Aerial Additive Building Manufacturing (£2,317,560) [52]. Overall, UON continues to be the mostly funded university over years. LU have climbed up in the ranking with steady progression in number of projects and it have now received similar total amount of funding as UOS. ICL is placed at the third place instead of last place in 2016, with highest growth rate in AM funding. UOC have obtained the least funding over years with the smallest amount of funding received in 2015 and 2016. Details on each mentioned projects can be found in the Appendix 9.3.

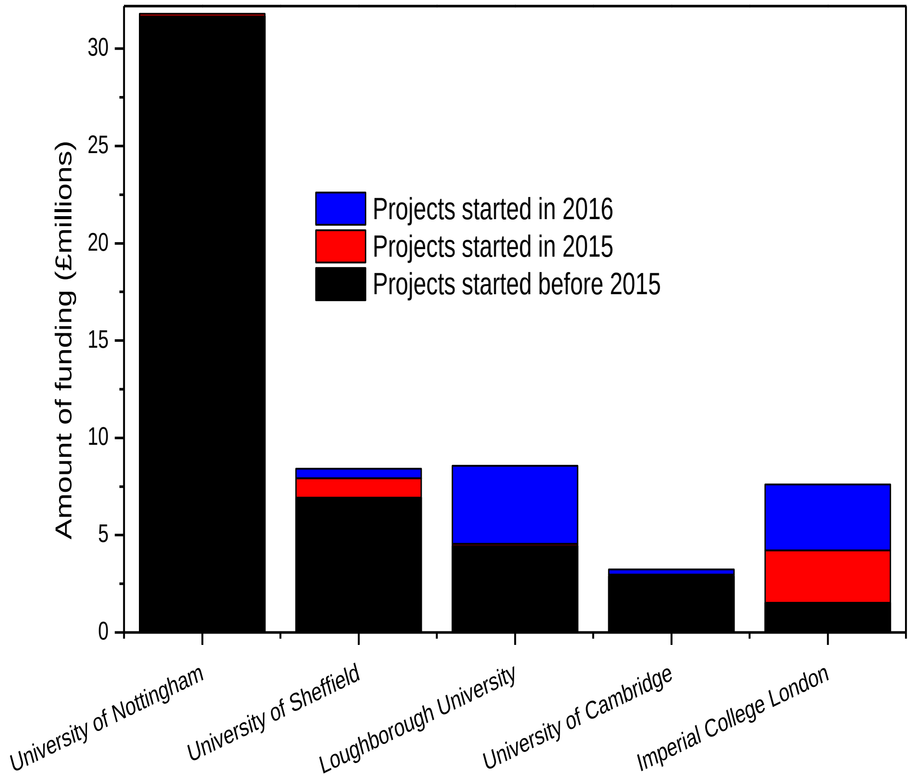


Figure 5-1: Amount of funding received by 5 selected UK universities

5.3. What is the research focus?

To take a closer look on recent trends in research topics, 5 selected universities are evaluated based on both number of research projects and publications on AM during 2015 and 2016. As shown in Table 5-2 and Table 5-3, similar trends can be found between these two metrics.

There are three primary research sectors stated in Figure 5-2, including: applications, material and process. Design, regulations and others together only contribute to a fraction of total AM research. UON received the highest amount of funding over years, have wide-spread interest over these five research topics and other 4 universities have different focus in AM research.

For application related research that uses AM techniques as a tool to manufacture products, it is heavily focused on medical and dental applications along with substantial interest on electronics, consumer goods and energy. Every selected university has both published or projects on AM application, mainly on FDM and SLM, but also with considerable attention on EBM and SLA and minor interest on SLS, SMD, PIJ and 2PL. There is also significant amount of projects and publications that looks into the general use of AM into various other industry, such as lattice structure. In comparison, LU have dedicated intensely on application of AM, and then followed by ICL, UOS and UON, lastly by UOC.

There is also a widespread study to understand properties of materials in various processes, technology and applications, such as characterisation of surface properties, fracture mechanism in material processing, development of new materials, use of mixed material. Currently, UOS is the one of the main players in material development and one of the key reason is that it owns more types of equipment than others, with extensive material input including polymer, metal, ceramics and organic materials. The other four universities are also competing strongly or moderately in this area. Some key examples include high performance metals, such as Titanium (Ti-6AL-4V) [53–58], Aluminium (AlSi12, AlSi10Mg) [55], or Nickel based alloy (CM247C) for SLM [59,60]; Multi-material for UAM [61–63] and PIJ (e.g. polycaprolactone [64–66] or latex [67]); cell laden hydrogel for bio-printer [68]. Furthermore, UOS have exclusive research published on Titanium (Ti-6AL-4V) for EBM [69–74], Nylon elastomers for HSS [75–77], Titanium (Ti-6AL-4V) for SMD [78–83] with exclusive ownership of these machine than others. There are some important topics that haven't been addressed much yet, such as recyclability and availability of materials.

In process development, AM research is aiming to understand key process in different machine, to develop or optimise the performance of machine and to integrate AM with non-AM technique. Compared to the high attention received in research on applications and materials, there are fewer publications on process development, but it has received strong interest from projects, revealing that majority of the work on process is currently under development. Again, the UOS have a clear advantage on process as it has a wide range of equipment available and is keen to improve the process of EBM and HSS. Some topics have attracted a lot of attention lately, such as in-situ process monitoring and meteorology, self-assembly of components, and bio-printing process. However there is still lack of study published on automation of process which is in great need by industry to boost productivity and efficiency.

Similar to the global and national trend in AM research, there is limited resources dedicated to design along with very little work on regulations. More input have to be allocated to improve on software, design guild lines, AM standards and regulation (e.g. IP), economic or environmental analysis on AM, in order to drive the commercialisation of AM technology. Some missing links have been recognised that LU have published a review of design for AM and UOC have a few publications on sustainability and economic implication of AM manufacturing.

Table 5-2: Mapping of the focus in research topics in the 5 selected universities based on projects 2015 - 2016

	Application	Materials	Process	Regulation	Design	Others
Loughborough University						
Nottingham University						
University of Sheffield						
University of Cambridge						
Imperial College London						
Sum						

*Data is collected via RCUK

Table 5-3 *Mapping of the focus in research topics in 5 selected university based no. publications 2015 -2016*

	Application	Materials	Process	Regulation	Design	Others
Loughborough University						
Nottingham University						
University of Sheffield						
University of Cambridge						
Imperial College London						
Sum						

*Data is collected via Scopus and based on 170 publications

Code of technology use	Very strong	Strong	Moderate	Moderate-low	Low	None or Unknown

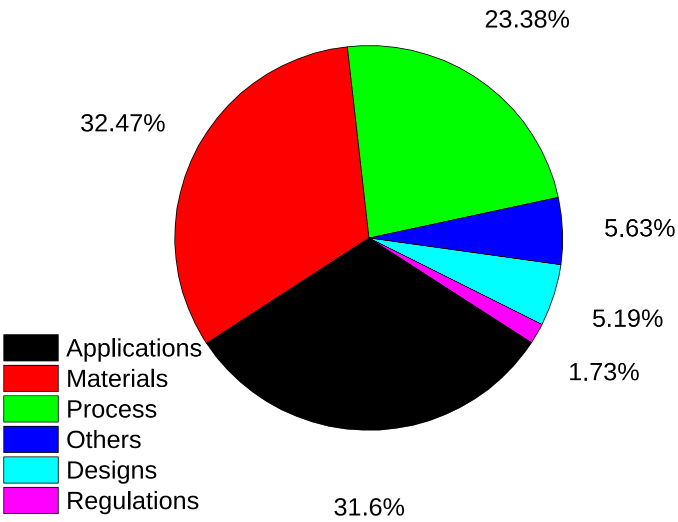


Figure 5-2: Research areas being studied by 5 selected universities from publications 2014-2016 via Scopus.

5.4. Overview

Based on the analysis of funding, equipment, publication and projects, an overview is shown in Figure 5-3. This figure is built on normalised data and more details on methodology can be found in the Appendix 9.3. It is shown that the UON have the highest competence over other universities that have great advantage in funding and publications, but limited funding has been reported in 2015 and 2016. LU and UOS continues to be on the top list that LU have an increasing number of projects and funding in these two years and UOS have the widest range of equipment available. ICL have been the fastest growing universities on AM universities so far, with four folds funding received in 2015 and 2016. In comparison, UOC will need a great improvement on funding, equipment and publications in order to compete with others.

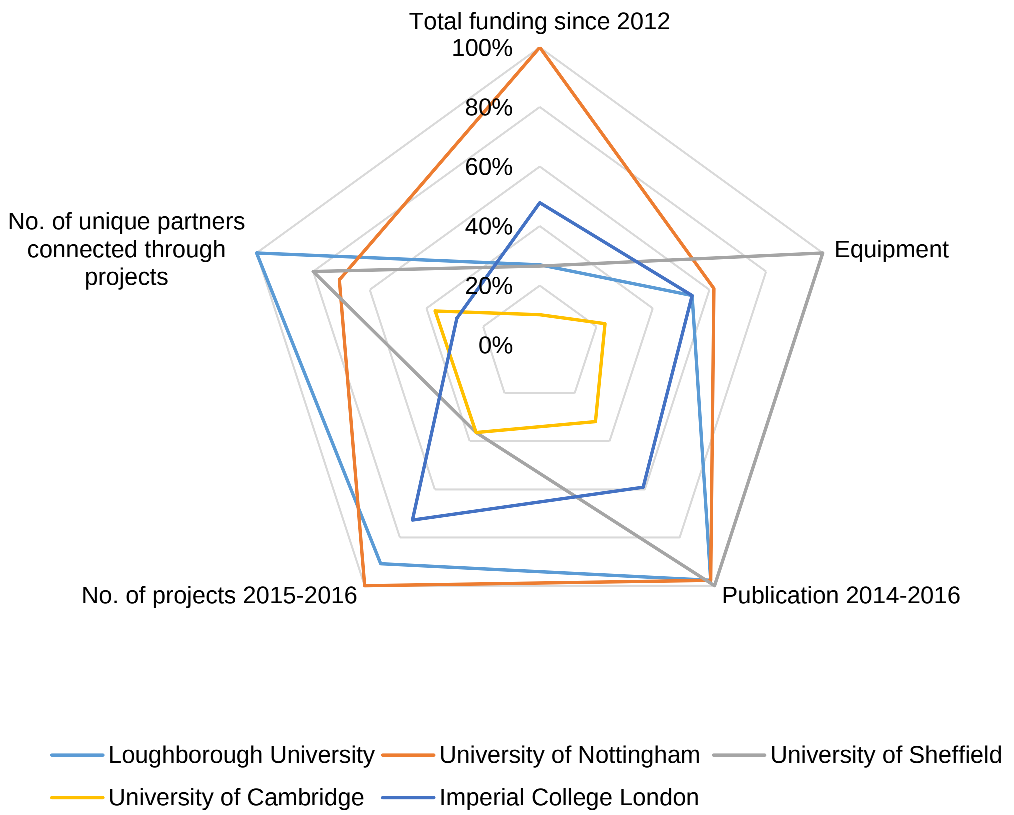


Figure 5-3: Overview of 5 selected universities based on normalised data

5.6 Conclusions

- These five selected UK universities have been involved in every category of AM technique which resembles well to the UK's national funding.
- PBF and ME machine are owned by every universities that every university now is competing heavily on SLM, to reach a technology breakthrough and FDM is widely studied for AM applications. SLS, PIJ, and SLA, are also popular and studied by most of the universities.
- UON has the highest reported funding, equipment and publications. Some unique machines are found in UON including LMJ, MMJ, and MPLA. Its research interest wide spread on different topics, with slight emphasis on material development.
- UOS has the widest reported range of equipment available and some exclusive AM machines are established in publications, such as EBM, IS, HSS, SMD, CBJ, SMD. UOS's AM research focus very strongly in material development, along with applications and process.
- LU is another leading university, with its funding doubled in 2015 and 2016. Its research have intensively used AM as a tool to manufacture products.
- ICL has been the fastest growing university in AM so far, with four fold increases in funding received in 2015 and 2016. Currently, it is focused more in applications and material development.
- The UK's AM research is weak on regulation, design, economic and environmental assessment, which could be the key to expand AM research and lead to commercialisation of AM technique.

- The academic collaborations within the UK's universities is mainly through EPSRC centre for Innovative Manufacturing in AM, with involvement from all 5 selected universities. This is primarily based at the University of Nottingham.

6. Conclusions

The UK is well placed to benefit from AM growth over the next 10 years, built on a strong foundation of engineering excellence. However, it is evident that there are a number of weaknesses, opportunities and threats that need to be addressed in order for the UK to maintain its position as a leading high value AM developer.

Over the last 10 years AM has witnessed considerable growth in numerous industrial sectors. Whilst penetration of AM into fields such as aerospace, automotive and medical have seen the largest increases, mass market penetration has still yet to be achieved due to a number of technical challenges, such as print speeds, accuracy/tolerances, and production volumes. These challenges present large research opportunities within the printing process stages. In the UK, there is research activity across the various AM technologies, and the UK excels in the research and development of novel AM technologies. However, the translation of this research into commercial impact has thus far been limited, in part, a consequence of limited successful UK based printing machine vendors.

Beyond developing printing machines and understanding the fundamental machine processes, the pre- and post-treatment operations are often overlooked. Many benefits of increased printing capabilities, such as geometric complexities, come at little extra cost to the printing stage; however they create significant economic burdens during the pre- and post-processing stages either directly or through time, computational or material costs. There is an increasing demand for methods to decrease pre- and post-processing times, optimise processes and methodologies, and lower their associated costs.

By evaluating global market trends, publication numbers, publication subject and funding allocation over recent years this report has identified potential AM research themes that have received little attention within the UK; but have large industrial implications and can draw from strong UK skills base in parallel research sectors. These are;

- IP protection
- Standards
- Education
- Unified data format and transformation
- AM design methodologies
- AM specific design tools
- Scientific appreciation of the fundamental processes
- Modelling
- Automation and optimisation of post-processing

Along with sustained double digit growth in global AM markets, AM research is anticipated to grow continuously in the next 10 years. The UK holds a prominent global position in the AM research community and is engaged in the development of both AM technology and applications, but far from leading in any one specific area. Globally, the UK is within the top 4 countries working on AM and are accompanied by the US, China and Germany. Within the EU, AM is clearly a priority area with €160 million worth of research funding invested, much of which the UK is involved with. The current EU funding in AM currently represents 18% of available funds and with the UK's decision to leave the EU, it is important to ensure that future research funds are secured to ensure the health of UK AM research.

Funding within the UK has been shown to exhibit a long tail effect, with a small number of institutions, receiving the majority of the research funding, though there are signs that this is shifting. The UK government and industry are committed to AM which has been identified as one of 22 priority technologies for high value manufacturing. £115 million is already allocated to AM research activities across a broad range of technologies, this amount has increased steadily since 2007 and shows no signs of abating.

Whilst, there is a healthy amount of industrial engagement, there is also evidence that there is limited cross-pollination of research activities. This report has found that the UK AM research community is fragmented. Despite the high growth in the number of participants, organisations are still only networking through loosely connected projects, with a limited open innovation culture. Thus, limited knowledge sharing of good practice, innovations and standards is in danger of creating barriers to research growth. It is recommended that a coordinate, collaborative, UK AM network is required to maintain excellence, avoid internal competition and duplication. In order to achieve this, an increased number of 'single point of contact' within industrial and academic institutions for AM research efforts would help enable a functional UK wide AM network. This issue has been recognised by the UK Government and governing NGOs, and steps have begun to form a UK AM strategy since 2015. It indicates that the UK government have started to take a more targeted and strategic approach, in order to maximise co-operation. A UK AM strategy will help identify the UK's strengths and weakness, and build a roadmap to expanding AM activities. It is vital that industry participation is included in this process.

The aim of the 2016 ICL AMN report was to identify and evaluate the current AM research landscape, both at an international and national level. It is hoped that this report can serve as an aid in a UK wide effort to map a national strategy in AM research. Future ICL AMN reports will take a more internal focus; looking at ICL's position and strategy for growth within the UK and global landscape.

7. Acknowledgements

The additive manufacturing network would like to thank:

- The Imperial College Faculty of Engineering Research Committee for funding the activities of the network.
- Audrey Gaulard for creation of the Infographics.
- The MTC and Canon 3D for fruitful discussions.
- Professor Peter Childs and Dr. Marco Aurisicchio for their respective comments.

8. References

[1] Technology Strategy Board, A landscape for the future of high value manufacturing in the UK, 2012.

[2] J. Faludi, Environmental impacts of 3D printing, Autodesk Educ. Community. (2013).

[3] T.T. Wohlers, Wohlers Report 2014: 3D printing and additive manufacturing state of the industry annual worldwide progress report, 2014.

[4] H. Blum, The future of 3D printing to 2025, (2015). http://www.smitherspira.com/news/2015/june/3d-print-market-expected-to-reach-$49b-by-2025 (accessed September 4, 2016).

[5] Wohlers Associates, Wohlers report 2012: Additive manufcaturing and 3D printing state of the industry, 2012.

[6] A. Vicari, R. Kozarsky, Building the Future: Assessing 3D Printing's Opportunities and Challenges, 2013.

[7] Roland Berger, Additive manufacturing - A game changer for the manufacturing industry?, n.d.

[8] J. Adolfsson, J. Manalili, J. Riikonen, J. Neoke, J. Salmela, T. Kobold, Additive manufacturing: 3D printing continue to get better and cheaper, n.d.

[9] M. KTN, Shaping Our National Competency in Additive Manufacturing Manufacturing Special, (2012).

[10] 3D Printing and Intellectual Property Law : Key Considerations, (2015) 1–8.

[11] Intellectual Property Office, 3D Printing - A Patent Overview, 2013. doi:10.1017/CBO9781107415324.004.

[12] W. Gao, Y. Zhang, D. Ramanujan, K. Ramani, Y. Chen, C.B. Williams, C.C.L. Wang, Y.C. Shin, S. Zhang, P.D. Zavattieri, The status, challenges, and future of additive manufacturing in engineering, Comput. Des. 69 (2015) 65–89. doi:10.1016/j.cad.2015.04.001.

[13] J. Ford, Ten minutes with RepAIR, the project bringing IVHM & additive manufacturing to aircraft maintenance, Eng. (2016).

[14] A. International, European Space Agency sponsors cold spray project at Trinity College Dublin, ASM Int. (2015).

[15] Overview of the factories of the future projects: progress through partnership, 2012.

[16] A.M.S.I. Group, Shaping our national competency in additive manufacturing, 2012.

[17] B. Krassenstein, BAAM 3D printer gets major upgrade - prints 100 lbs of material per Hour & more, 3DPRINT.COM. (2015).

[18] M. Matisons, New York State to build $125 Million industrial-scale 3D printing plant in partnership with Norsk Titanium, 3DPRINT.COM. (2015).

[19] China developing world's largest 3D printer, prints 6m metal parts in one piece, 3D Printers 3D Print. News. (2014).

[20] Cranfield University, WAAM, (2016). https://www.cranfield.ac.uk/case-studies/research-case-studies/waammat.

[21] The international conference that delivers the credible voice of additive manufacturing & 3D printing, (n.d.).

[22] International Conference on additive manufacturing & 3D printing, EPSRC Cent. Innovavative Manuf. Addit. Manuf. (2015).

[23] High Speed Sintering, Univ. Loughbrgh. (2016).

[24] R. Hague, P. Reeves, S. Jones, Mapping UK research and innovation in additive manufacturing, 2016.

[25] T. Wohler, Wohlers Report 2016, 2016.

[26] P. Reeves, D. Mendis, The current status and impact of 3d printing within the industrial sector: an analysis of six case studies, 2015.

[27] Funding competition: connected digital additive manufacturing, Innov. UK. (2016).

[28] D. Espalin, D.W. Muse, E. MacDonald, R.B. Wicker, 3D printing multifunctionality: structures with electronics, Int. J. Adv. Manuf. Technol. 72 (2014) 963–978. doi:10.1007/s00170-014-5717-7.

[29] A.J. Lopes, E. MacDonald, R.B. Wicker, Integrating stereolithography and direct print technologies for 3D structural electronics fabrication, 18 (2012) 129–143. doi:10.1108/13552541211212113.

[30] C.J. Robinson, B. Stucker, A.J. Lopes, R. Wicker, J.A. Palmer, Integration of direct-write (DW) and ultrasonic consolidation (UC) technologies to create advanced structures with embedded electrical circuitry, in: University of Texas at Austin (freeform), 2006: pp. 60–69.

[31] L. Mortara, J. Hughes, P.S. Ramsundar, F. Livesey, D.R. Probert, Proposed classification scheme for direct writing technologies, Rapid Prototyp. J. 15 (2009) 299–309. doi:10.1108/13552540910979811.

[32] C. Ladd, J.-H. So, J. Muth, M.D. Dickey, 3D printing of free standing liquid metal microstructures, Adv. Mater. 25 (2013) 5081–5085. doi:10.1002/adma.201301400.

[33] K.H. Church, C. Fore, T. Feeley, Commercial applications and review for direct write technologies, MRS Proc. 624 (2000) 3. doi:10.1557/PROC-624-3.

[34] K.K.B. Hon, L. Li, I.M. Hutchings, Direct writing technology—Advances and developments, CIRP Ann. - Manuf. Technol. 57 (2008) 601–620. doi:10.1016/j.cirp.2008.09.006.

[35] Manufacturing Technology Centre, Manuf. Technol. Cent. (2015).

[36] R. Bowerman, Meeting with personal correpondance from MTC, (2016).

[37] J. He, Meeting with personal correpondance from Renishaw, (2016).

[38] Hybrid Manufacturing Technologies, Hybrid Manuf. Technol. (2016).

[39] R. McCutcheon, R. Pethikc, B. Bono, M. Thut, 3D printing and the new shape of industrial manufacturing, (2014) 8.

[40] P. Strikwerda, HP launches 3d printers with Multi Jet Fusion™ technology, 3D PRINTING.COM. (2016).

[41] 3D Printing Drives Manufacturing Innovation at Lockheed Martin, (2014).

[42] B. Wire, Canon strengthens its 3d proposition through strategic partnership with materialise, Bus. Wire. (2016).

[43] L.R. Hart, S. Li, C. Sturgess, R. Wildman, J.R. Jones, W. Hayes, 3D printing of biocompatible supramolecular polymers and their composites, 8 (2016) 3115–3122. doi:10.1021/acsami.5b10471.

[44] EPSRC, Foresight fellowship in manufacturing - the future of additive manufacturing, EPSRC. (n.d.).

[45] EPSRC launches Fellowships for the Future of Manufacturing, EPSRC. (n.d.).

[46] Catapult high value manufacturing, CATAPULT. (2016).

[47] Department for Education, 3D printers in schools: uses in the curriculum, (2013).

[48] Laser-based engineering of paper for manufacturing fluidic sensors: (Lab-flo), EPSRC. (2015).

[49] 3D bioplotter for biological tissue development, Res. Counc. UK. (2015).

[50] Advanced acrylate based hybrid materials for osteochondral regeneration, EPSRC. (2015).

[51] Additive manufacturing of advanced medical devices for cartilage regeneration: minimally invasive early interventio, EPSRC. (2016).

[52] Aerial additive building manufacturing, EPSRC. (2016).

[53] T.B. Kim, S. Yue, Z. Zhang, E. Jones, J.R. Jones, P.D. Lee, Additive manufactured porous titanium structures: Through-process quantification of pore and strut networks, J. Mater. Process. Technol. 214 (2014) 2706–2715. doi:10.1016/j.jmatprotec.2014.05.006.

[54] Z. Zhang, L. Yuan, P.D. Lee, E. Jones, J.R. Jones, Modeling of time dependent localized flow shear stress and its impact on cellular growth within additive manufactured titanium implants, 102 (2014) 1689–1699. doi:10.1002/jbm.b.33146.

[55] N.T. Aboulkhair, I. Maskery, C. Tuck, I. Ashcroft, N.M. Everitt, On the formation of AlSi10Mg single tracks and layers in selective laser melting: Microstructure and nano-mechanical properties, 230 (2016) 88–98. doi:10.1016/j.jmatprotec.2015.11.016.

[56] M.. Simonelli, Y.Y.. Tse, C.. Tuck, Microstructure of Ti-6Al-4V produced by selective laser melting, J. Phys. Conf. Ser. 371 (2012). doi:10.1088/1742-6596/371/1/012084.

[57] J.. Vaithilingam, R.D.. Goodridge, R.J.M.. Hague, S.D.R.. Christie, S.. Edmondson, The effect of laser remelting on the surface chemistry of Ti6al4V components fabricated by selective laser melting, J. Mater. Process. Technol. 232 (2016) 1–8. doi:10.1016/j.jmatprotec.2016.01.022.

[58] J.. J. Vaithilingam, R.D.R.D.. Goodridge, R.J.M.R.J.M.. Hague, S.D.R.S.D.R.. Christie, S.S.. Edmondson, The effect of laser remelting on the surface chemistry of Ti6al4V components fabricated by selective laser melting, J. Mater. Process. Technol.

232 (2016) 1–8. doi:10.1016/j.jmatprotec.2016.01.022.

[59] N.J. Harrison, I. Todd, K. Mumtaz, Reduction of micro-cracking in nickel superalloys processed by Selective Laser Melting: A fundamental alloy design approach, 94 (2015) 59–68. doi:10.1016/j.actamat.2015.04.035.

[60] V.D. Divya, R. Muñoz-Moreno, O.M.D.M. Messé, J.S. Barnard, S. Baker, T. Illston, H.J. Stone, Microstructure of selective laser melted CM247LC nickel-based superalloy and its evolution through heat treatment, 114 (2016) 62–74. doi:10.1016/j.matchar.2016.02.004.

[61] T. Monaghan, A.J. Capel, S.D. Christie, R.A. Harris, R.J. Friel, Solid-state additive manufacturing for metallized optical fiber integration, Compos. Part A Appl. Sci. Manuf. 76 (2015) 181–193. doi:10.1016/j.compositesa.2015.05.032.

[62] J. Li, T. Monaghan, S. Masurtschak, A. Bournias-Varotsis, R.J. Friel, R.A. Harris, Exploring the mechanical strength of additively manufactured metal structures with embedded electrical materials, Mater. Sci. Eng. A. 639 (2015) 474–481. doi:10.1016/j.msea.2015.05.019.

[63] A. Bournias-Varotsis, R.A. Harris, R.J. Friel, The effect of ultrasonic excitation on the electrical properties and microstructure of printed electronic conductive inks, in: Proc. Int. Spring Semin. Electron. Technol., 2015: pp. 140–145. doi:10.1109/ISSE.2015.7247978.

[64] P.S.P. Poh, D.W. Hutmacher, B.M. Holzapfel, A.K. Solanki, M.A. Woodruff, Data for accelerated degradation of calcium phosphate surface-coated polycaprolactone and polycaprolactone/bioactive glass composite scaffolds, 7 (2016) 923–926. doi:10.1016/j.dib.2016.01.023.

[65] P.S.P. Poh, D.W. Hutmacher, B.M. Holzapfel, A.K. Solanki, M.M. Stevens, M.A. Woodruff, In vitro and in vivo bone formation potential of surface calcium phosphate-coated polycaprolactone and polycaprolactone/bioactive glass composite scaffolds, 30 (2016) 319–333. doi:10.1016/j.actbio.2015.11.012.

[66] K.A. Blackwood, N. Ristovski, S. Liao, N. Bock, J. Ren, G. Kirby, M.M. Stevens, R. Steck, M.A. Woodruff, Improving electrospun fibre stacking with direct writing for developing scaffolds for tissue engineering for non-load bearing bone, in: Springer Verlag, 2015: pp. 125–128. doi:10.1007/978-3-319-11776-8_31.

[67] M.. Lukic, J.. Clarke, C.. Tuck, W.. Whittow, G.. Wells, Printability of elastomer latex for additive manufacturing or 3D printing, J. Appl. Polym. Sci. 133 (2016). doi:10.1002/app.42931.

[68] L.E. Bertassoni, J.C. Cardoso, V. Manoharan, A.L. Cristino, N.S. Bhise, W.A. Araujo, P. Zorlutuna, N.E. Vrana, A.M. Ghaemmaghami, M.R. Dokmeci, A. Khademhosseini, Direct-write bioprinting of cell-laden methacrylated gelatin hydrogels, 6 (2014). doi:10.1088/1758-5082/6/2/024105.

[69] S. Tammas-Williams, P.J. Withers, I. Todd, P.B. Prangnell, Porosity regrowth during heat treatment of hot isostatically pressed additively manufactured titanium components, 122 (2016) 72–76. doi:10.1016/j.scriptamat.2016.05.002.

[70] S. Tammas-Williams, P.J. Withers, I. Todd, P.B. Prangnell, The effectiveness of hot isostatic pressing for closing porosity in titanium parts manufactured by selective electron beam melting, 47 (2016) 1939–1946. doi:10.1007/s11661-016-3429-3.

[71] I. Farina, F. Fabbrocino, G. Carpentieri, M. Modano, A. Amendola, R. Goodall, L. Feo, F. Fraternali, On the reinforcement of cement mortars through 3D printed polymeric and metallic fibers, 90 (2016) 76–85. doi:10.1016/j.compositesb.2015.12.006.

[72] A. Amendola, E. Hernández-Nava, R. Goodall, I. Todd, R.E. Skelton, F. Fraternali, On the additive manufacturing, post-tensioning and testing of bi-material tensegrity structures, 131 (2015) 66–71. doi:10.1016/j.compstruct.2015.04.038.

[73] S. Tammas-Williams, H. Zhao, F. Léonard, F. Derguti, I. Todd, P.B. Prangnell, XCT analysis of the influence of melt strategies on defect population in Ti-6Al-4V components manufactured by Selective Electron Beam Melting, 102 (2015) 47–61. doi:10.1016/j.matchar.2015.02.008.

[74] C.J. Smith, M. Gilbert, I. Todd, F. Derguti, Application of layout optimization to the design of additively manufactured metallic components, (2016) 1–17. doi:10.1007/s00158-016-1426-1.

[75] A. Ellis, C.J. Noble, N. Hopkinson, High Speed Sintering: Assessing the influence of print density on microstructure and mechanical properties of nylon parts, 1 (2014) 48–51. doi:10.1016/j.addma.2014.07.003.

[76] A. Ellis, C.J. Noble, L. Hartley, C. Lestrange, N. Hopkinson, C. Majewski, Materials for high speed sintering, 29 (2014) 2080–2085. doi:10.1557/jmr.2014.156.

[77] A. Ellis, L. Hartley, N. Hopkinson, Effect of Print Density on the Properties of High Speed Sintered Elastomers, 46 (2015) 3883–3886. doi:10.1007/s11661-015-2833-4.

[78] U. Woy, S. Jones, R. Gault, K. Ridgway, R. McCluskey, Evaluation of Shaped Metal Deposition (SMD) for applications in the energy industry, in: 2014: pp. 619–622.

[79] G. Escobar-Palafox, R. Gault, K. Ridgway, Preliminary empirical models for predicting shrinkage, part geometry and metallurgical aspects of Ti-6Al-4V shaped metal deposition builds, in: 2011. doi:10.1088/1757-899X/26/1/012002.

[80] G. Escobar-Palafox, R. Gault, K. Ridgway, Robotic manufacturing by shaped metal deposition: State of the art, 38 (2011) 622–628. doi:10.1108/01439911111179138.

[81] B. Baufeld, O. Van der Biest, R. Gault, Additive manufacturing of Ti-6Al-4V components by shaped metal deposition: Microstructure and mechanical properties, 31 (2010). doi:10.1016/j.matdes.2009.11.032.

[82] A.K. Swarnakar, O. Van Der Biest, B. Baufeld, Young’s modulus and damping in dependence on temperature of Ti-6Al-4V components fabricated by shaped metal deposition, 46 (2011) 3802–3811. doi:10.1007/s10853-011-5294-1.

[83] B. Baufeld, Mechanical properties of INCONEL 718 parts manufactured by shaped metal deposition (SMD), 21 (2012) 1416–1421. doi:10.1007/s11665-011-0009-y.

9. Appendix

9.1. Methodology and data for Chapter 3

The collected data on global research trend in section 3.2 is based on online research via Scopus (https://www.scopus.com/) on 14th July unless specifically cited. This is based on different key words as shown in Table 9-1. The number of publication on Additive manufacturing (or 3d Printing) collected here is referred to global scale, including article, conference paper, review, book chapter and article in Press. To be noted, all the information in section 3.2 is limited to 2014 to 2016 to observe the most recent trend in AM research, except Figure 3-5. Figure 3-5 looks at the amount of total publication from 1965 to 2016. This analysis do not take into account of the impact factor due to complexity to weigh in and lack of unified and consistent terminology for different AM techniques.

Table 9-1 Scopus search for Chapter 3

	Key words
Figure 3-5: Total number of AM publications globally per year	Your query : ((TITLE-ABS-KEY(additive manufacturing) OR TITLE-ABS-KEY(3D printing)))
Figure 3-6: The top 20 countries that work on AM research Figure 3-7: The top 13 authors in AM research Figure 3-8: The top 20 organisations that work on AM research internationally	Your query : ((TITLE-ABS-KEY(additive manufacturing) OR TITLE-ABS-KEY(3D printing)) AND (LIMIT-TO(PUBYEAR,2016) OR LIMIT-TO(PUBYEAR,2015) OR LIMIT-TO(PUBYEAR,2014)))
Figure 3-9: The total number of publications worldwide of various AM techniques Figure 3-10: Number of publications the top 10 countries in each field Figure 3-11: Number of publications by different countries divided into niche AM technologies	Individual search for each AM technology with its full name For example for SLM technology: Your query : ((TITLE-ABS-KEY(additive manufacturing) OR TITLE-ABS-KEY(3D printing) AND TITLE-ABS-KEY(selective laser melting) OR TITLE-ABS-KEY(Direct metal laser sintering))) AND (LIMIT-TO(PUBYEAR,2016) OR LIMIT-TO(PUBYEAR,2015) OR LIMIT-TO(PUBYEAR,2014)))

9.2. Methodology and data for Chapter 4

The collected data on UK's AM publication in section 4 is based on online research via search tool Scopus (https://www.scopus.com/) on 30th July unless specifically cited. This search tool used different key words as shown in Table 9-2. The number of publication on Additive manufacturing (or 3d Printing) collected here is referred to national scale, including article, conference paper, review, book chapter and article in Press. To be noted, all the information in section 4 is limited to 2014 to 2016 to observe the most recent trend in AM research, except Figure 4-1. Figure 4-1 looks at the amount of total publication from 1965 to 2016. This analysis do not take into account of the impact factor due to complexity to weigh in and lack of unified and consistent terminology for different AM techniques.

Table 9-2 Scopus search for Chapter 4

Figure 4-1: Number of AM publications in the UK	Your query : ((TITLE-ABS-KEY(additive manufacturing) OR TITLE-ABS-KEY(3D printing)) AND (LIMIT-TO(AFFILCOUNTRY,"United Kingdom")))
Figure 4-5: Geographic distribution of key universities that work on AM research based on the amount of publications in 2014-2016 via Scopus. 5 coloured universities have been selected for in-depth analysis. Figure 4-6: Top 15 UK universities on AM research based on number of publications from 2014-2016 via Scopus Figure 4-7: Number of AM publications by UK based authors via Scopus (2014-2016)	Your query : ((TITLE-ABS-KEY(additive manufacturing) OR TITLE-ABS-KEY(3D printing)) AND (LIMIT-TO(PUBYEAR,2016) OR LIMIT-TO(PUBYEAR,2015) OR LIMIT-TO(PUBYEAR,2014)) AND (LIMIT-TO(AFFILCOUNTRY,"United Kingdom"))) All the publications found were summarised in Mendeley library for selected universities. Then each publication was sorted into different research areas and different AM equipment, with criteria explained in Table 9-3; they were also tagged accordingly in Mendeley library. The results is summarised

Figure 4-2 is the summary of projected funding on AM research in UK, which is contributed form three sources. Innovate UK 2015 report have discussed the amount of funding which have been allocated or declared for the period 2017 to 2022. For the projects included in this subsection had to meet all of the following criteria [24]:

- The project had either received funding from a non-commercial source (government or charity) or involved a non-commercial research organisation as a partner (university, government technology laboratory or regional technology organisation)
- The project involved at least one UK-based partner
- The project was / is active during the period September 2012 to September 2022
- The project involved at least one element of research relating to advancing the field of additive manufacturing.

As more funding have been allocated/declared after 2014, new data are added into Figure 4-2. For the additional funding in 2015, it is based on an online search on Research Councils UK

(RCUK) website with keywords as "additive manufacturing" or "3D printing", with funding start year of 2015. This search is conducted on 1st June 2016.

Table 9-3 Definition for classification of research areas

Research areas	
Application	Using AM technology as a tool to manufacture product
Materials	Understanding properties of material in different process/application eg. surface properties, facture mechanism, developing new materials, use of mixed material, recyclability, biocompatibility
Process	Understanding the process in different machine, development or optimise the performance of machine eg. automation, integrated process of AM & non-AM tech,
Design/Optimisation	Design and software, modelling, optimisation
Standard/Regulation	Understanding and development of AM standards, policy and regulation
Others	Include Cost Analysis / product value/ Finance/energy input, benchmarking, review, education

A summary of all selected projects are summarised in Table 9-4 to produce a grand total funding in 2015, with details of lead participant, funded value, funded period, funder, project category and project reference number for each project.

Table 9-4 AM projects funded in 2015 in UK (RCUK web search)

Ranking	Title	Lead research organisation	Funded value (GBP)	Funded period	Project Ref
1	Operational Development Cell for EBM (Electron Beam Melting) - FILTON	GKN Aerospace Services Limited	1,850,000	2015-2017	113062
2	TiPOW (Titanium Powder for Net-shape Component Manufacture)	GKN Aerospace Services Ltd	1,555,610	2015-2018	113051
3	Personalised Stent Graft Manufacturing for Endovascular Intervention	Imperial College London	1,249,590	2014-2018	EP/L020688/1
4	Large Volume, Multi-material High Speed Sintering Machine	University of Sheffield	892,226	2015-2017	EP/M020827/1
5	Novel Multiple Materials Additive Manufacturing Instrument for New Generation of Optical fibre Fabrication	University of Southampton	700,271	2015-2018	EP/M020916/1
6	University of Glasgow Experimental Equipment proposal (3D printed electronics)	University of Glasgow	697,986	2015-2016	EP/M028135/1
7	Advanced acrylate based hybrid materials for osteochondral regeneration	Imperial College London	606,488	2015-2018	EP/M019950/1

8	ProbeTools: Digital Devices for User Research	Goldsmiths College	591,558	2015-2017	EP/M015327/1
9	Laser-based engineering of paper for manufacturing fluidic sensors: (Lab-flo)	University of Southampton	586,822	2015-2018	EP/N004388/1
10	Additive Manufacturing Next Generation Supergen Energy Storage Devices	Manchester Metropolitan University	509,085	2015-2019	EP/N001877/1
11	3DP-RDM: Defining the research agenda for 3D printing enabled re-distributed manufacturing	University of Cambridge	467,623	2015-2016	EP/M017656/1
12	haRFest	Pragmatic Printing Limited	357,584	2015-2016	102154
13	Live imaging of virus assembly and release by simultaneous, correlative topographical and fluorescence confocal microscopy	Imperial College London	350,458	2015-2018	BB/M022080/1
14	Laser-based engineering of paper for manufacturing fluidic sensors: (Lab-flo)	Imperial College London	308,071	2015-2018	EP/N00468X/1
15	HI-PROSPECTS - HIgh resolution PRinting Of Solar Photovoltaic EleCTrode Structures	Swansea University	300,702	2015-2018	EP/N509905/1

16	Extending the Potential for the Digitally Printed Ceramic Surface	Royal College of Art	267,150	2015-2017	AH/M004333/1
17	HI-PROSPECTS - HIgh resolution PRinting Of Solar Photovoltaic EleCTrode Structures	Queen Mary, University of London	247,698	2015-2018	EP/N509917/1
18	Advanced Acrylate-Based Hybrid Materials for Osteochondral Regeneration	University of Warwick	219,274	2015-2018	EP/M020002/1
19	Development of a digital printing technology demonstrator for the additive manufacturing of textiles	Alchemie Technology Limited	215,018	2015-2017	720627
20	Next Generation Manufacturing of 3D Active Surface Coatings	Keele University	205,572	2015-2017	EP/M020738/1
21	Biofabrication and characterisation of a new class of functional and durable auricular cartilage implants	Swansea University	201,388	2015-2018	MR/N002431/1
22	3D Bioplotter for Biological Tissue Development	Imperial College London	171,455	2015-2016	BB/M012662/1
23	The University of Huddersfield and Paxman Coolers Limited	University of Huddersfield	168,141	2015-2018	509575
24	Whispering Gibbon: Automated Game Asset Merchandising	Whispering Gibbon Limited	156,050	2015-2016	720491

25	Foresight Fellowship in Manufacturing: Defining and Fabricating New Passive Bio-Sensing Wireless Tag Technologies	University of Kent	148,602	2015-2016	EP/N009118/1
26	Foresight Fellowship in Manufacturing: Analytical technologies in continuous and additive manufacturing	University of Nottingham	132,415	2015-2017	EP/N009126/1
27	Offset lithographic printing of nanocomposite graphene ink	Nano Products Limited	104,017	2015-2016	131795
28	Organic/Inorganic Hybrid 'Bioinks' for 3D Bioprinting	The University of Manchester	100,149	2015-2017	EP/M023877/1
29	CAT International Limited - Development of 3D printing machine for carbon and carbon composite articles	Cat International Ltd	100,000	2015-2016	710755
30	Rapid Prototyping of High Strength Geosynthetic Interfaces	Loughborough University	99,433	2015-2016	EP/M015483/1
31	High resolution, multi-material deposition of tissue engineering scaffolds	University of Cambridge	99,393	2015-2016	EP/M018989/1
32	Engineering smart 3D silk fibroin tissue culture scaffolds using reactive inkjet printing	University of Sheffield	99,250	2015-2016	EP/N007174/1

33	New generation of manufacturing technologies: liquid print of composite matrices	University of Bristol	97,378	2015-2017	EP/M009149/1
34	The first validation of personalised dosimetry for molecular radiotherapy using 3D printed organs - Invited resubmission.	The University of Manchester	96,766	2015-2016	ST/M004589/1
35	A Low-Cost Medium-Range 3D Scanner	Cadscan Limited	88,917	2015-2016	720614
36	Digital Printing Media Preparation	Technijet Limited	83,258	2015-2016	720666
37	Life-3D: A New Tool for Interactive Visualisation of 3D Molecular Interaction	University of Portsmouth Higher Education Corporation	80,000	2015-2016	971422
38	University of Wolverhampton and Industrial Penstocks Limited	University of Wolverhampton	63,300	2015-2017	509267
39	Offset lithographic printing of nanocomposite graphene ink.	Nottingham Trent University	46,903	2015-2016	EP/M507763/1
40	D2ART: Transforming Disability Arts Through Digital Technologies	University of Birmingham	39,688	2015-2016	AH/M010414/1
41	Remanufacturing and Reuse of Industrial Printing Press Printheads	Camscience	35,000	2015-2016	132074
42	Low-Cost, High Accuracy 3D Scanning	Cadscan Limited	24,999	2015	700529

43	Micro-Cellular 3D Printing Filament	In-Cycle Ltd	23,100	2015	131929
44	Optical Fabrication and Imaging Facility for three-dimensional sub-micron designer materials for bioengineering and photonics	Imperial College London	10,526	2015-2017	EP/M000044/1
45	Formulation advice - 3D printing food	Nufood Industries Limited	5,000	2015-2016	753052
46	3D Manufacturing	Auto Service Tools Limited	5,000	2015-2016	753009
47	Development of a Metallurgical 3D Printer	Photocentric Limited	5,000	2015-2016	752970
48	The Chocolate Tree	The Chocolate Tree	5,000	2015	752566
49	3DP Rapid manufacture tooling	3d printing engineering	5,000	2015	752443
50	digital printing metallic colours onto textiles	mh collection	5,000	2015-2016	752012
51	Kidesign IP support	Kidesign	5,000	2015-2016	753111
52	A CAD framework for product development	Carduino Ltd	5,000	2015	752045
	Sum for 2015 projects		14,488,914		

Similar process and criteria is used to generate 2015 data using RCUK website. Extra funding call have been announced in 2016. Details of these projects are summarised in Table 9-5. There is about additional £4.5 million funding call announced in 2016 June and allocated for "connected digital additive manufacturing" from Innovate UK, which is also added into Table 9-5.

Table 9-5 AM projects funded in 2016 in UK (RCUK web search)

Ranking	Title	Lead research organisation	Funded value (GBP)	Funded period	Project Ref	FirstName	Research topics
1	WIng DesigN methodologY validation (WINDY)	Airbus Operations Limited	8,787,840	2016-2019	113074	Caroline Kingston	Other General, Application
2	SYnthesizing 3D METAmaterials for RF, microwave and THz applications (SYMETA)	Loughborough University	4,012,830	2016-2021	EP/N010493/1	Yiannis Vardaxoglou	3d print electronics, Application,
3	Formulation for 3D printing: Creating a plug and play platform for a disruptive UK industry	University of Nottingham	3,531,770	2016-2020	EP/N024818/1	Ricky Wildman	Other General, Material
4	Aerial Additive Building Manufacturing: Distributed Unmanned Aerial Systems for in-situ manufacturing of the built environment	Imperial College London	2,317,560	2016-2020	EP/N018494/1	Mirko Kovac	Other General, Application, Material, Design
5	Evaporative Drying of Droplets and the Formation of Micro-structured and Functional Particles and Films	Durham University	2,270,300	2016-2020	EP/N025245/1	Colin David Bain	Other General, material

6	REMASTER - REpair Methods for Aerospace STructures using novEl pRocesses	Rolls-Royce plc	1,742,390	2016-2018	102380	David Currier	Other General, appplication, material, process
7	Reliable Additive Manufacturing technology offering higher ProdUctvity and Performance (RAMP-UP)	Reliance Precision Limited	1,138,960	2016-2018	102572	Ian laidler	Other General, Application, proccess, material
8	Additive manufacturing of advanced medical devices for cartilage regeneration: minimally invasive early intervention	Imperial College London	1,057,130	2016-2019	EP/N025059/1	Julian Jones	Biomedical application, application
9	High Efficiency Recuperator for stationary power Micro-Turbine (HERMiT)	HiETA Technologies Limited	910,886	2016-2018	102593	Stephen Mellor	Other General, Application
10	High temperature, affordable polymer composites for AM aerospace applications	Victrex Manufacturing Limited	810,713	2016-2018	102362	Adam Chaplin	Other General, material, application, process
11	Imaging Cardio-Mechanical Health	King's College London	670,825	2016-2019	EP/N011554/1	David Nordsletten	Biomedical application, application
12	Engineering Fellowships for Growth - Morphogenesis Manufacturing: Smart Materials With Programmed Transformations	University of Bath	628,702	01/02/2016	EP/M002489/2		Other General, process, deisgn
13	Novel high performance polymeric composite	University of Exeter	624,707	2016-2019	EP/N034627/1	Yanqiu Zhu	Other General, Material

	materials for additive manufacturing of multifunctional components						
14	Solid INTERface Batteries - SINTER	University of Sheffield	333,657	2016-2019	EP/N023579/1	Xiubo Zhao	3D print electronics, Application, material
15	Novel high performance polymeric composite materials for additive manufacturing of multifunctional components	University of Ulster	325,687	2016-2019	EP/N034783/1	Eileen Harkin-Jones	Other General, Material
16	Development of a clinical 3D printing based patient-specific MRT dosimetry system	The University of Manchester	318,947	2016-2019	ST/P000150/1	David Matthew Cullen	Biomedical application, application
17	ADAM: Anthropomorphic Design for Advanced Manufacture	University of Nottingham	269,486	2016-2017	EP/N010280/1	Ian Ashcroft	Design
18	Fabrication of antibody functionalized silk fibroin micro-well arrays using reactive inkjet printing for circulating tumour cell capture	University of Cambridge	262,231	2016-2017	EP/N005953/1	James Moultrie	Biomedical application
19	Eva â€“ Development of the first low cost, light weight, plug and play tabletop robotic arm	AUTOMATA TECHNOLOGIES LIMITED	240,403	2016-2017	720797	Suryansh Chandra	Other General, application

20	Improving biological integration of osseous and dermal tissues in macaque cranial implants	Newcastle University	214,565	2016-2019	NC/P000940/1	Alexander Thiele	Biomedical application, material
21	Additive Manufacturing for Cooled High-Temperature Automotive Radial Machinery (CHARM)	HiETA Technologies Limited	209,319	2016-2017	132229	Helen Bliss	Other General, Application
22	Advanced Inverted Brayton Cycle exhaust heat recovery with Steam Generation	HiETA Technologies Limited	198,834	2016-2017	132225	Simon Jones	Other General, application
23	Inkjet Printing of Plasma Functionalised Graphene to Deliver Multifunctional Polymer Composites for Aerospace Applications (PlasmaGraph)	Netcomposites Limited	183,678	2016-2017	132259	Beverly Frain	Other General, material, appliaation, proccess
24	Inkjet Printing of Plasma Functionalised Graphene to Deliver Multifunctional Polymer Composites for Aerospace Applications (PlasmaGraph)	Netcomposites Limited	183,678	2016-2017	132259	Beverly Frain	Other General, application, material, process
25	Camshaft Lightweighting through Advanced Manufacturing (CLAMP)	JD Norman Lydney Ltd	183,426	2016-2017	132219		Other General, Application

26	Prototype Development of a Hybrid Gas and Ultrasonic Powder Delivery Syste,	Advanced Laser Technology Ltd	157,581	2016-2017	720754	Roger Hardacre	Other General, process
27	Prototype Development of a Hybrid Gas and Ultrasonic Powder Delivery Syste,	Advanced Laser Technology Ltd	157,581	2016-2017	720754	Roger Hardacre	Other General, material, process
28	STLX (AM design to AM machine to enable ditributed manufacutring process)	Grow Software Ltd	141,621	2016-2017	720802	Katherine Prescott	Other General, application, design, process
29	Low-cost Spatial Beam Combination enabling UV Laser Diode Arrays for Stereolithography	Applied Materials Technology Limited	104,619	2016-2017	132202	Iain Glass	Other General, process
30	ESSENCE: Embedding Softness into Structure Enabling Distributed Tactile Sensing of High-order Curved Surfaces	King's College London	100,549	2016-2017	EP/N020421/1	Hongbin Liu	Other General, application
31	Integrated Microwave Amplifiers for Electrosurgical Applications	The University of Manchester	99,244	2016-2017	EP/N019628/1	Christopher Duff	Biomedical application, application
32	Virtual Testing of Additively-Manufactured Hybrid Metal-Composite Structures	University of Bristol	99,084	2016-2017	EP/M021963/1	Luiz Kawashita	Biomedical application, application, material, design
33	THINGS3D LIMITED - Digital Rights Management and Brokerage	Things3D Limited	99,055	2016-2017	710815	Chris Byatte	Design/regulation/others

	Platform for Personalised Smart 3D Printed Licensed Products						
34	Design for Additive Manufacturing (D4AM)	Queen's University of Belfast	98,942	2016-2017	EP/N030540/1	Jesus Martinez del Rincon	Design/regulation/others
35	Investigating pressure induced conductive states on the nanoscale : A novel route to nano-circuitry	Queen's University of Belfast	98,734	2016-2017	EP/N018389/1	Amit Kumar	3D print electronics, process
36	Layered Extrusion of Metal Alloys (LEMA)	University of Sheffield	98,456	2016-2017	EP/M022218/1	Kamran MUMTAZ	Other General, material, process
37	A 3D printing solution to solve parents pain with orthotics services	Project Andiamo Limited	94,514	2016-2017	710839	Naveed Parvez	Biomedical application, application
38	The University of Sheffield and LPW Technology Limited (bespoke alloys for metallic Additive Manufacturing)	University of Sheffield	93,882	2016-2018	509808		Other General, material, process
39	NuAIR stent: A respiratory stent inspired by nature, achieved through cutting edge architecture and engineering	Northwick Park Institute for Medical	76,075	2016-2017	710781	Tahera Ansari	Biomedical application, application
40	Advancing the Commercial Applications of Graphene	University of Sheffield	70,402	2016-2017	EP/P510233/1	Patrick Smith	Other General, Material
41	Road Accident 3D Reconstruction	Roke Manor Research Limited	17,273	2016-2017	132277	Dean Thomas	Other General, Application

	Sum for 2016 projects		33,036,136				

The amount of funding for per technology in Figure 4-9 and Figure 4-11is given by Innovate UK 2015 report, then re-arranged into 7 standard AM technology and summarised in Table 9-6.

The selected projects included in Figure 4-3 had also to meet all of the criteria used in Innovate UK 2015 report, and then categorise them into four different types as following:

- 3D-printed electronics: the project is connected to how to apply AM techniques to produce electronics
- Biomedical applications: the project is about how to apply AM techniques in biomedical applications
- General materials/process/application: other research interests on AM materials, process or application (see Table 9-3 for definitions)
- Design/regulations/ others: other research interests on design, regulations or others (see Table 9-3 for definitions).

Table 9-6 Funding for various AM technology

Funding source	PBF			DED		MBJ	ME	VAT-P		SL	Multiple-technology or can't identify	Grand total
	SLM	EBM	SLS	LMD	MWF	Jetting	FDM	SLA	2PL			
EPSRC	2,258,092		468,556	558,909		5,633,222	583,421				23,972,356	33,474,556
Industry	3,443,351	200,161	1,521,691	3,137,092	638,427	2,416,155	52,267	58,076		158,601	18,338,099	29963920
FP7	452,109	829,055	1,726,397	3,970,192		1,002,024		251,688		545,065	10,801,689	19578219
Innovate UK	3,762,562		1,188,314	1,345,933	655,039		608,931				8,885,495	16446274
University	448,132		336,056	127,782		563,349	144,786				9,931,321	11551426
DSTL						189,568	36,362				1,550,064	1775994
Others	222,000			84,000				677,000	74,549		726,545	1784094
Grand total	10,586,246	1,029,216	5,241,014	9,223,908	1,293,466	9,804,318	1,425,767	986,763	74,549	703,666	74,205,569	114,574,482
Sum	16,856,476			10,517,374				1,061,312				

9.3. Methodology for Chapter 5

Information on AM research projects and their available 3D printing facility in each selected university is gathered both from their own their university's website on 1st June, as in Figure 9,and their publications and projects mentioned in Chapter 3.

To be noted, University of Cambridge do not have a specific site or group contributed to AM research, so limited information was able to be found. The collected information is then summarised in Figure 9-1, and sort into different research areas with the same criteria described in chapter 3 and Table 9-3 based on their online description.

Table 9-7 AM research group in selected UK Universities

	Name of research group	Website
Loughborough University	Additive Manufacturing Research Group	http://www.lboro.ac.uk/research/amrg/
University of Nottingham	Additive Manufacturing and 3D Printing Research Group	https://www.nottingham.ac.uk/research/groups/3dprg/index.aspx
University of Sheffield	Centre for Advanced Additive Manufacturing	http://www.adamcentre.co.uk/
University of Cambridge	The Technology Enterprise Group	http://www.ifm.eng.cam.ac.uk/research/teg/digital-fabrication/
Imperial College London	Additive Manufacturing Network	http://www.imperial.ac.uk/additive-manufacturing/

Loughborough University

- CassaMobile
- Ceramic Packages
- Bespoke Flow Reactor
- Medical Modelling
- Richard III
- ArtiVasc 3D
- Direct Digital Fabrication
- Additive Manufacturing of Novel Multi-functional Metal Matrix Composites Materials
- Photobioform
- Sasam

Nottingham University

- Design Systems Development for Multifunctional Additive Manufacturing
- ALSAM
- ASID
- ALMER
- Metrology for Additive Manufacturing
- Jetting of reactive inks
- Developing Models that can Accurately Simulate the Delivery, Deposition and Post-Deposition Behaviour of Materials
- 3D Cell Modelling
- Area Sintering for Multifunctional Additive Manufacturing
- Jetting of Conductive and Dielectric Elements to Enable Multifunctional Additive Systems
- Nano-functionalised Optical Sensors (NANOS) Jetting of Conductive and Dielectric Elements to Enable Multifunctional Additive Systems

University of Sheffiled

- Large Volume, Multi-material High Speed Sintering Machine
- Engineering smart 3D silk fibroin tissue culture scaffolds using reactive inkjet printing
- Anchorless Selective Laser Melting (ASLM) of high temperature metals
- Direct digital fabrication via multisystems integration of advanced manufacturing processes

University of Cambridge

- High resolution, multi-material deposition of tissue engineering scaffolds
- 3DP-RDM: Defining the research agenda for 3D printing enabled re-distributed manufacturing
- Laser Induced Transfer for Printed Electronics Devices (LITPED
- Innovation in industrial inkjet technology

Imperial College London

- 3D printed fuel cell
- Understanding conductivity and porosity in metal 3D printed parts
- Integrated Computational Materials Engineering (ICME) approach for Metal-based Additive Manufacturing

Figure 9-1 Summary of AM research projects in UK University that published on website

To look at the AM equipment capability for each selected universities, data was sorted from gathered online information, research projects and publication (Table 9-4, Table 9-5, Figure 9-2, Table 9-8) are grouped together in Table 9-10; then Table 5-1 was produced and coloured coded each university from strong to week by the variety of equipment. The criteria for colour coding in Table 5-1 coding is explained as following:

Code of technology use	Strong (>10)		Moderate (5-10)		Low (1-5)		Available/Published	✓

The sum of funding for 5 selected universities in Figure 5-1 is calculated by adding up the total funding from Innovate UK 2015 report and RCUK analysis in 2015 & 2016 (Table 9-4 and Table 9-5) for each university respectively, except ICL. To be noted, funding for ICL is purely based on RCUK analysis as information is not available in 2015Innovate UK report. The data on funding is summarised in Table 9-13.

Table 5-2 is constructed based on information about projects in 2015 and 2016.only. Each project is sorted into different research areas based on the criteria mentioned in Table 9-3. Then the number of projects for each research area for each selected university is summarised in Table 9-9. Repetitive projects will be only considered as one.

The colour coding for Table 5-2 and Table 5-3 is explained as following:

Code of technology use	Very strong (>20)	Strong (15-20)	Moderate (10-15)	Moderate-low (5-10)	Low (1-5)	None or Unknown (0)

A research network is built for 5 selected university in Figure 9-2 , Figure 9-3, Figure 9-4, Figure 9-5, and Figure 9-6 respectively based on the Mendeley results from Scopus research mentioned in chapter 3 and 4. The research network also includes examples of key projects. The focus in each research area is colour coded according to the criteria discussed in Table 9-3. A summary of no. of publications from 2014 to 2016 by AM equipment and research areas is given in Table 9-12 and then produce Table 5-3 and Figure 5-2.

Table 9-10 Summary of the number of projects in 5 selected university on different research area

Table 9-13 Summary of normalised data for 5 selected Universities

	Application	Materials	Process	Regulation	Design	Others
Loughborough University	7	3	1	1	0	0
Nottingham University	1	1	4	1	5	1
University of Sheffield	2	7	7	0	1	0
University of Cambridge	4	4	3	1	0	1
Imperial College London	8	4	1	0	3	0
Sum	22	19	16	3	9	2

The data on equipment, funding, projects and partners for each university were also summarised in Figure 9-14. Then each data point was normalised against the highest value for each category and concluded in Figure 9-13 and Figure 5-3 was produced.

Table 9-11 Summary of available facility in selected UK universities

Type of machine	PBF				MJ					BJ	ME	VAT-P		SL	Sum
	SLM/DMLS	EBM	SLS	IS	PIJ	WIJ	OIJ	LMJ	MMJ	CBJ	FDM	SLA	MPLA	UC	
University of Sheffield	1	2	1	1	2		1			2		1		2	13
University of Nottingham								1	1				1		3
Loughborough University	1		2			1					3	1			8
University of Cambridge															0
Imperial College London	2		5		7		1				11	1			27
Sum	4	2	8	1	9	1	2	1	1	2	14	3	1	2	51

Table 9-12 Summary of research areas in selected UK universities based on projects

	Application	Materials	Process	Standard/Regulation	Design/Optimisation	Cost
Loughborough University	5	3	1	1	0	0
Nottingham University	0	1	4	0	5	0
University of Sheffield	0	3	3	0	1	0
University of Cambridge	2	3	3	1	0	1
Imperial College London	2	1	0	0	0	0
Sum	9	11	11	2	6	1

Table 9-13 Summary of publication on AM within 4 selected universities

Research area	PBF				DED	MJ			ME		VAT-P		SL	Others	sum
	SLM/DMLS	EBM	SLS	IS	MWF	PIJ	HSS	EHD-JP	FDM	Bio-P	SLA	2 PL	UAM		
Application															
University of Nottingham	3					2			5		1			2	13
University of Sheffield		5			1	2			1		3			4	16
Loughborough University	5		1						9		1			5	21
University of Cambridge	1													4	5
Imperial College London	4		1					1	6	2	1	1		2	18
sum	13	5	2	0	1	4	0	1	21	2	6	1	0	17	
Materials															
University of Nottingham	11					4			1					4	20
University of Sheffield	1	9	4		1	1	6				2			1	25
Loughborough University	6		1			2							3		12
University of Cambridge	2		1												3
Imperial College London	2					1		1	8	2				1	15
sum	22	9	6	0	1	8	6	1	9	2	2	0	3	6	
Process															
University of Nottingham	6													6	12
University of Sheffield	1	8	3	1	2		5								20
Loughborough University	1					1					1		2	2	7
University of Cambridge	1		1											2	4
Imperial College London	3		1					1	3	2				1	11
sum	12	8	5	1	2	1	5	1	3	2	1	0	2	11	
Regulation															
University of Nottingham														1	1
University of Sheffield															0

Loughborough University														2	2
University of Cambridge														1	1
Imperial College London															0
Sum	0	0	0	0	0	0	0	0	0	0	0	0	0	4	
Design															
University of Nottingham	1					1								1	3
University of Sheffield		2													2
Loughborough University													1	5	6
University of Cambridge															0
Imperial College London	1														1
sum	2	2	0	0	0	1	0	0	0	0	0	0	1	6	
Others															
University of Nottingham	1					1								1	3
University of Sheffield														1	1
Loughborough University														1	1
University of Cambridge														6	6
Imperial College London														2	2
sum	1	0	0	0	0	1	0	0	0	0	0	0	0	11	
Total	99	48	26	2	8	29	22	6	66	12	18	2	12	99	231

Table 9-13 Summary of data for 5 selected Universities

	projects started before 2015	Projects started at 2015	projects started in2016	Research funding in AM since 2012	No. of unique partners connected through projects
University of Nottingham	31,657,000	132415	0	31789415	65
University of Sheffield	6,933,250	991476	497941	8422667	46
Loughborough University	4,447,730	99433	4012830	8559993	52
University of Cambridge	2,877,960	99393	262231	3239584	24
Imperial College London	1,527,655	2696588	3374690	15197866	19

Table 9-14 Summary of normalised data for 5 selected Universities

	Total Funding since 2012	Equipment	Publication 2014-2016	No. of projects 2015-2016	Funding (projects started before 2015)	Funding (projects started in 2015 & 2016)	No. of unique partners connected through projects
Loughborough University	27%	54%	98%	91%	14%	68%	100%
University of Nottingham	100%	62%	98%	100%	100%	2%	71%
University of Sheffield	26%	100%	100%	36%	22%	25%	80%
University of Cambridge	10%	23%	32%	36%	9%	6%	37%
Imperial College London	48%	54%	59%	73%	5%	100%	29%

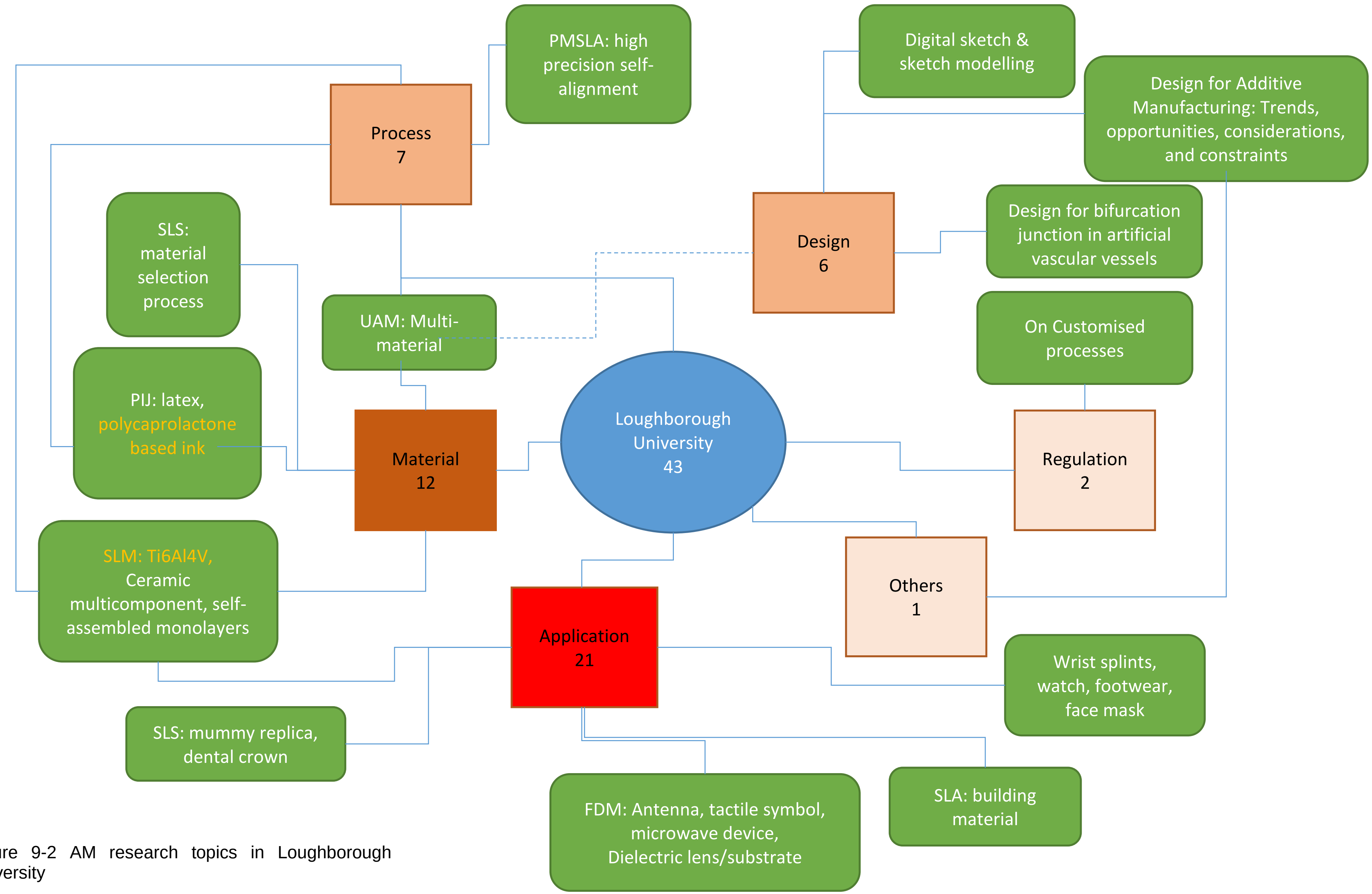


Figure 9-2 AM research topics in Loughborough University

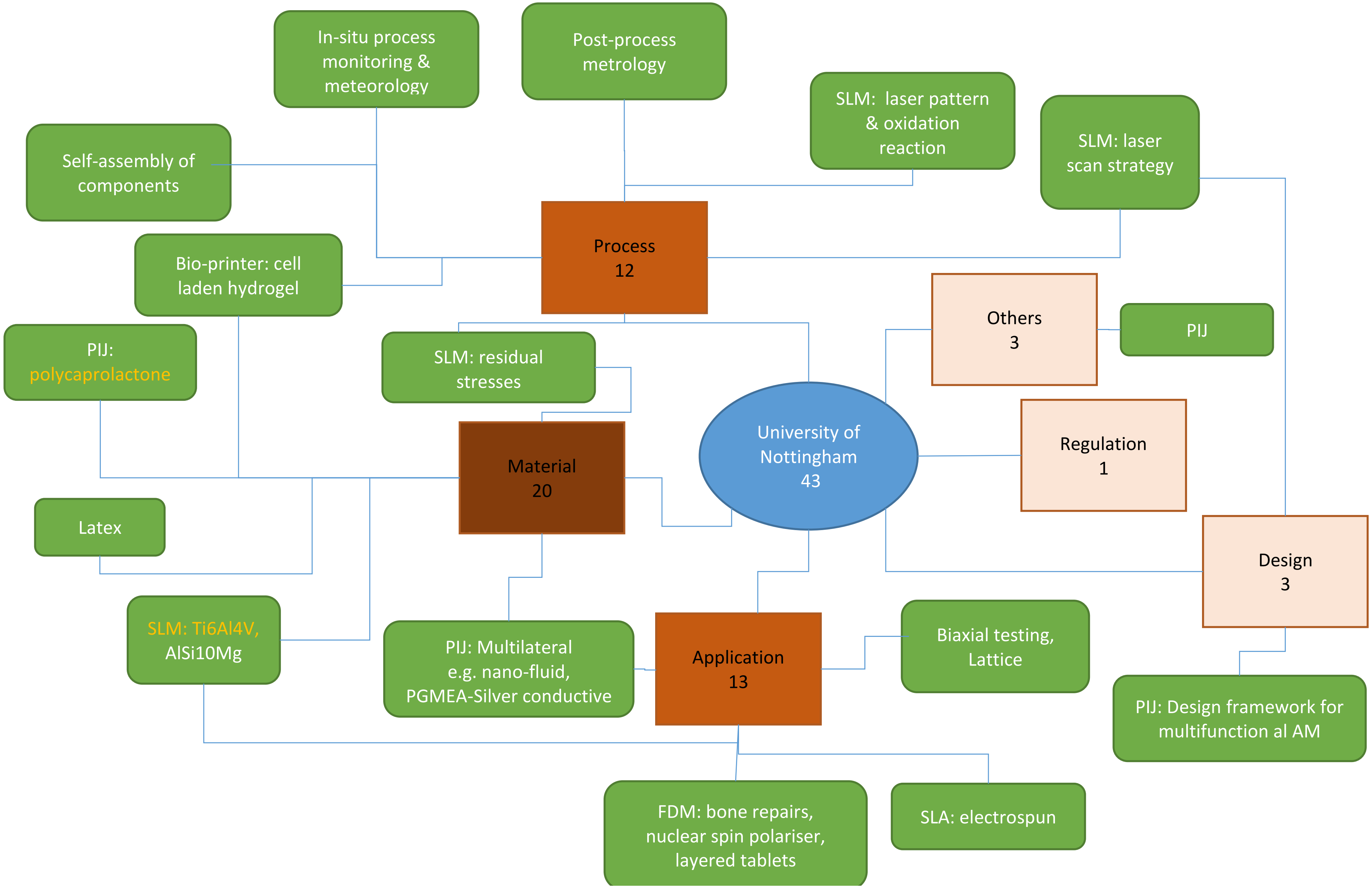


Figure 9-3 AM research topics in University of Nottingham

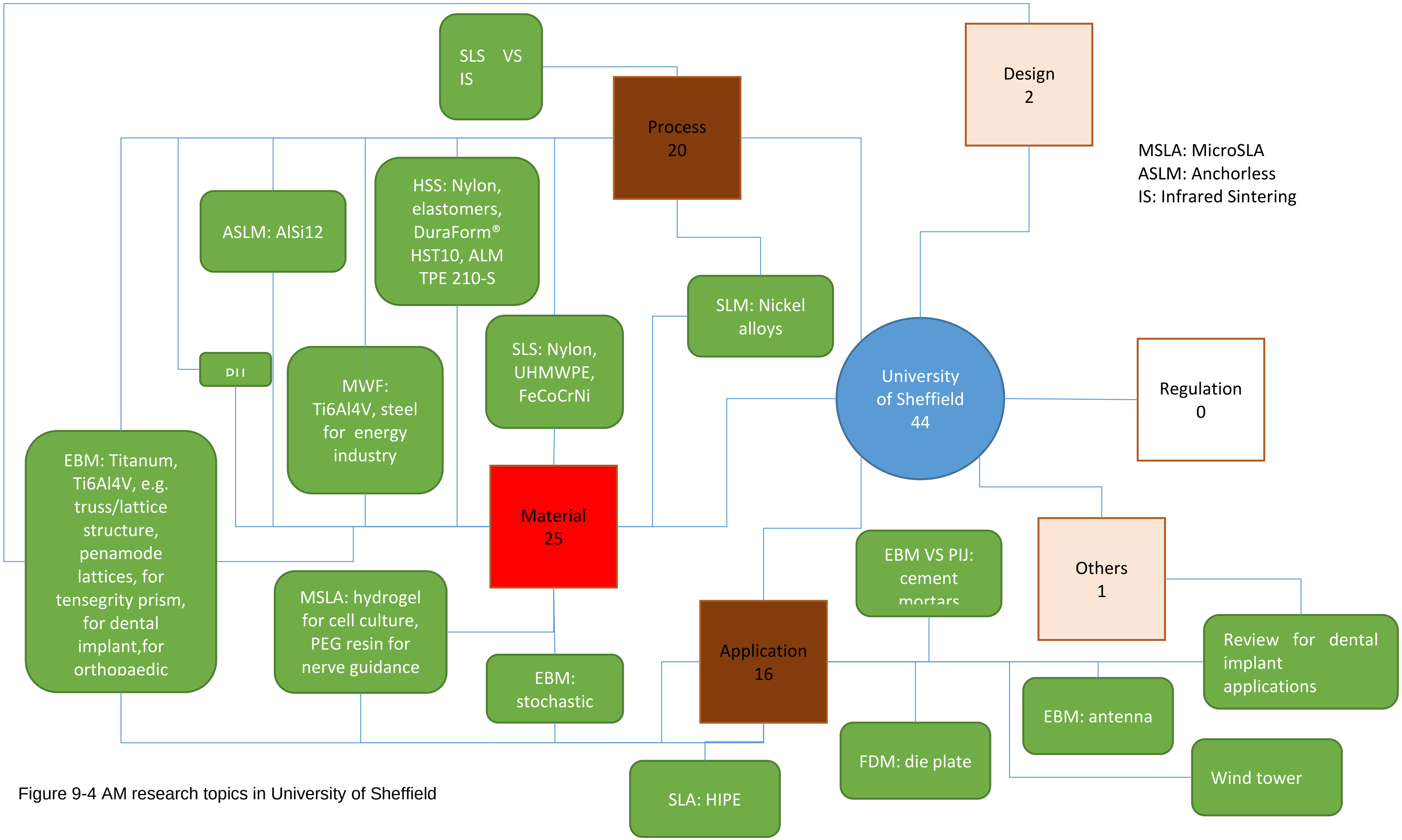


Figure 9-4 AM research topics in University of Sheffield

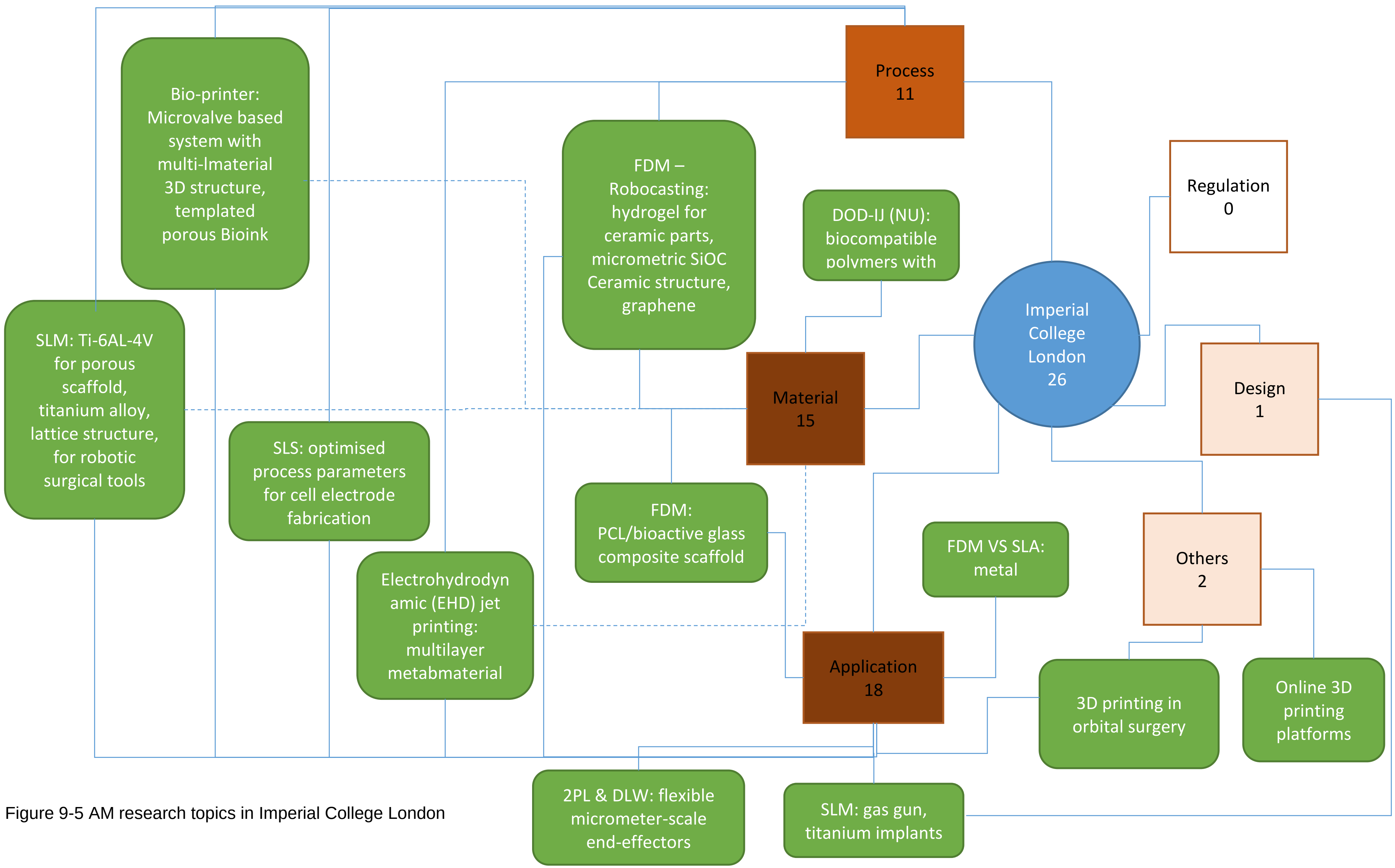


Figure 9-5 AM research topics in Imperial College London

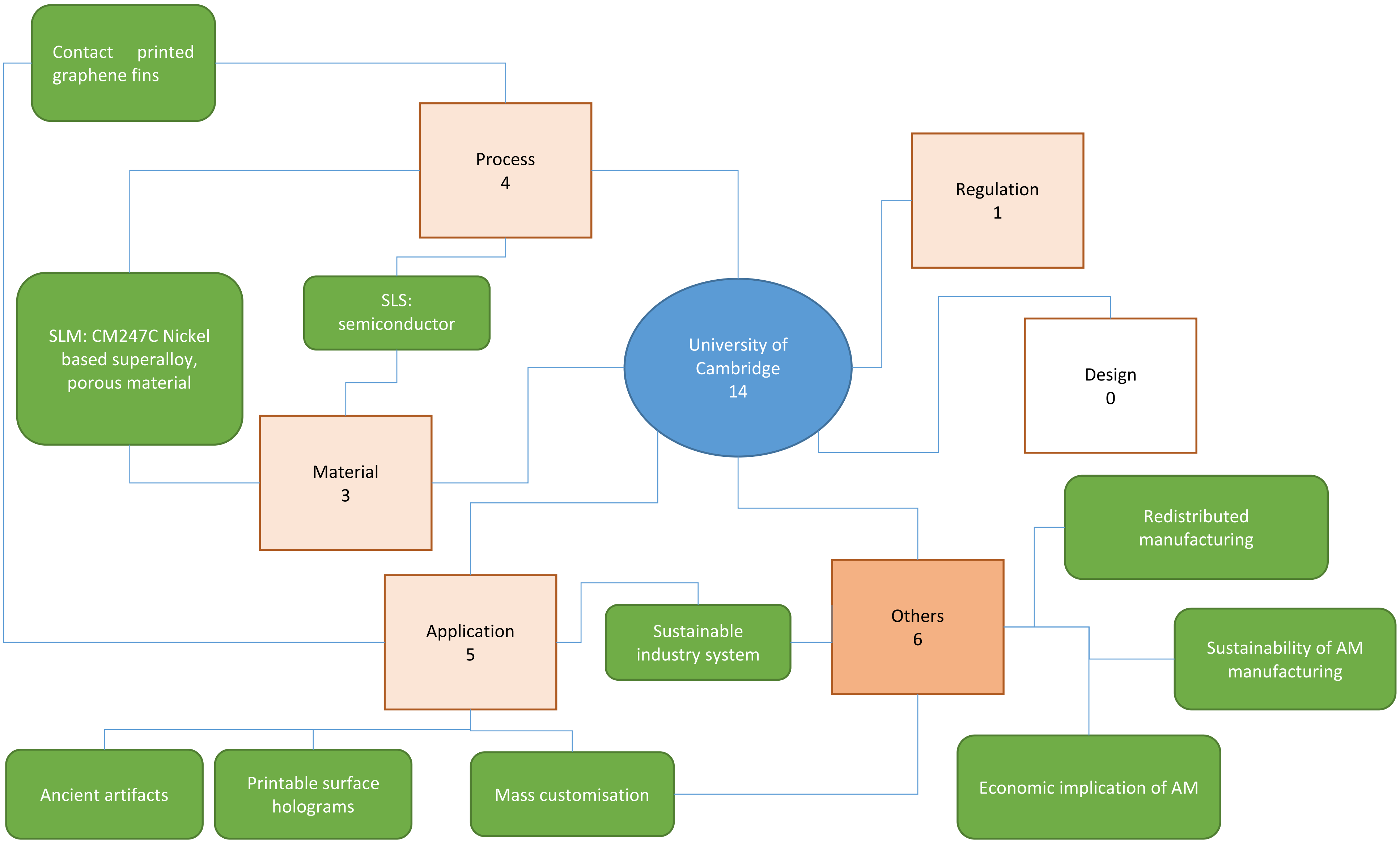


Figure 9-6 AM research topics in University of Cambridge