Mapping UK Research and Innovation in Additive manufacturing

A review of the UK's publicly funded R&D activities in additive manufacturing between 2012 and 2015

February 2016

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Executive Summary

Background to this report

Additive manufacturing – commonly referred to as 3D printing – describes the production of tangible objects using a wide variety of digitally controlled manufacturing machines. Over the last 30 years, additive manufacturing has become an underpinning technology for high value manufacturing. The additive manufacturing industry, including machine and material sales as well as associated services was valued at $3.07billion in 2013 and is predicted to grow to $21billion by 2020, with adoption in key sectors such as aerospace, medical devices, automotive and the creative industries. The technology was originally used mainly for model making and rapid prototyping; in the last 15 years it has been widely adopted for tool and mould making but in more recent years has emerged as a serious contender as an industrial process able to make end-use parts, offering a wide range of benefits to society including mass customisation, reduced environmental impact and enhanced design freedoms. The UK has been a world-leader in developing this technology and has pioneered applications for its commercialisation.

In September 2012, Innovate UK (formerly the Technology Strategy Board) published the report *"Shaping our National Competency in Additive manufacturing"* on behalf of the additive manufacturing Special Interest Group (SIG 2012)[1] which presented a definitive view of the state of additive manufacturing research within the UK. It concluded that the UK's research community was well-established and equipped but that there was a need to consolidate the research activities and develop a strategy for additive manufacturing within the UK in order to drive commercialisation of the technology for end-use parts.

The objective of this "*Mapping Additive manufacturing Research in the UK"* report is to follow up on the SIG 2012 report by mapping the current state of additive manufacturing research in the UK and understanding how the research landscape has changed since its publication. By analysing the publicly funded research projects that have been undertaken since 2012, this report identifies where the profile of research activity has changed within the UK, what shifts have taken place within the primary research actors and institutions and the industry sectors engaged in research, where the UK is strongest in additive manufacturing research and where there are current or emerging gaps in the research base.

Findings of this report

The results of this analysis are positive, demonstrating high growth in the UK's additive manufacturing research activities. **Additive manufacturing research funding has seen a 100% increase**, growing from the £15 million committed in 2012 to almost £30 million spent on research in 2014. Moreover, by February 2015, some £25 million of funding had already been committed to projects taking place this calendar year.

This funding has been attributed to 244 research projects, representing an **80% increase in the number of research projects** identified in the SIG 2012 report. A similar positive trend is seen when looking at the number of organisations involved in research projects which has **increased 200% to 243 organisations.** Most of this growth has come from greater engagement within commercial organisations, resulting in **higher engagement from the additive manufacturing supply chain**. In 2012, there were 57 commercial organisations involved in additive manufacturing research - a figure which has now grown to 165 commercial organisations. There has also been an increase in the number of academic institutions engaging in research, with 24 universities identified in 2012, compared to 41 universities in 2015.

This broad uptake indicates that many of the barriers to the adoption of additive manufacturing and limitations of the technology identified in the SIG 2012 report are being addressed. The concerns raised in 2012 relating to missing links in the additive manufacturing supply chain appear to be lessening, as there is now higher engagement from a wider range of sectors and supply chain actors such as software and materials development organisations. However, there is still **low commercial exploitation of the technology**, with only one global additive manufacturing machine manufacturer. The report also finds that a significant proportion of the UK's publicly funded additive manufacturing research is **focussed on the fundamental sciences** of additive manufacturing technology. The majority of research investment has been made where there in is an undefined application area or beneficiary sector, such as in the development of enabling technology or materials for additive manufacturing.

Despite a high growth in the number of participants involved in additive manufacturing research, **the additive manufacturing community is highly fragmented** with organisations only networking through projects rather than through a structured network, community of interest or association. Although the existing informal network contains centres of critical mass with significant amounts of funding focussed on specific research topics, there is also an extreme long tail effect, with a high number of partners involved in small projects, who are largely isolated from the larger research groups. With such a loosely connected additive manufacturing network, this could raise concerns about the strategic direction of the community and the cohesion between the members. Of course there is no guarantee that networking or knowledge sharing will stimulate or accelerate research outcomes. In some cases working in isolation will yield the best results. However, a properly structured network could go some way to eliminate duplication of research effort or prevent the dilution of research funding, which would then strengthen the UK's global position.

Recommendations from this report

To strengthen the UK's position in additive manufacturing and drive forward commercialisation of the technology, the following recommendations are made.

1. **A national strategy for developing the UK's additive manufacturing industry is essential to align the increasing number and diverse skillsets of participants within the additive manufacturing ecosystem and provide direction for research objectives.**

2. **A formal network of additive manufacturing users and developers should be established to provide cohesion between the participants in UK additive manufacturing research, facilitate knowledge transfer and act as a focal point for additive manufacturing in the UK.**

3. **Wherever appropriate, end users of innovations in additive manufacturing processes, materials and design systems should be closely involved in fundamental science research at an early stage.**

4. **Initiatives to provide skills and education for the UK's future additive manufacturing industry should be continued and widened.**

Contents

What is Additive Manufacturing?

Additive manufacturing – commonly referred to as 3D printing – describes the production of tangible objects using a wide variety of digitally controlled manufacturing machines. Unlike traditional manufacturing methods where material is removed from a solid block, additive manufacturing technologies build products layer-by-layer, only adding material where it is needed. “Additive manufacturing” is an umbrella term that refers to a range of different technologies, each with their own advantages, disadvantages and applications. This variety of technologies enables a wide range of materials to be processed, including polymers, metals, ceramics and bio-materials. First commercialised in the late 1980s, additive manufacturing technology initially found widespread usage in producing prototypes and tooling; this is now a well-developed application of the technology. In recent years, industry has begun moving towards using the technology for end-use part production, however this presents a number of challenges. A significant amount of research is still required to resolve technical issues as well as economic barriers to full-scale adoption.

What advantages does additive manufacturing offer?

Since the Industrial Revolution, society has embraced mass manufacturing, a concept driven by economies of scale, where the investment in dedicated tooling and machinery is recouped by producing a high volume of parts. Whilst this enables companies to provide consumers with products at low cost, it limits the choices available to the individual. Additive manufacturing represents a paradigm shift in manufacturing, bringing a range of technical, economic and social benefits.

Low volume production and mass personalisation

As a ‘tool-less’ and digital technology, additive manufacturing enables a move from mass production into mass customisation. Products can be produced in batches of one, without any cost penalty, allowing manufacturers to meet their customers’ requirements exactly. When coupled with 3D scanning technologies, completely personalised products such as hearing aids and implants can be economically manufactured.

Complex products with increased value

By building products in layers, additive manufacturing technologies are not constrained by many of conventional manufacturing’s limitations and so enable the manufacture of products with increased levels of geometric complexity. Designers are able to exploit the benefits offered by these new design freedoms and add value into their product; complex shapes such as lattices or topologically optimised structures can increase the functionality and performance of a product.

Reduced environmental impact

The complex geometries enabled by additive manufacturing can also result in products that have a lower environmental burden. This can be achieved by reducing the amount of raw material required to manufacture a part or by improving the efficiency of a product over its lifecycle. The aerospace and automotive industries are now using additive manufacturing to reduce weight and improve the fuel efficiency of their engines.

Distributed manufacture and new supply chains

In the same way that the internet has changed how consumers access music and film, additive manufacturing offers the potential to change how consumers access tangible products. By integrating additive manufacturing platforms with the internet, consumers can engage in the design process of products. These products can then be manufactured at a location close to the consumer, instead of in a centralised factory. From file-sharing platforms hosting printable content to networks of 3D printers around the world, new supply chains and business models are being created by businesses and consumers.

Types of additive manufacturing technology

The American Society for Testing and Materials (ASTM) has classified additive manufacturing technologies using seven top level process categories, as shown below. Despite new additive manufacturing technologies being invented, these have all fallen into one of the seven defined categories.

Additive manufacturing process categories

- Binder jetting — in which a liquid bonding agent is selectively deposited to join powder materials.
- Directed energy deposition—in which focused thermal energy is used to fuse materials by melting as they are being deposited.
- Material extrusion— in which material is selectively dispensed through a nozzle or orifice.
- Material jetting — in which droplets of build material are selectively deposited.
- Powder bed fusion —in which thermal energy selectively fuses regions of a powder bed.
- Sheet lamination — in which sheets of material are bonded to form an object.
- Vat photopolymerization—in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

From ASTM standard F2792-12[2]

Table 1 details the classification of key additive manufacturing technologies that have either been commercialised or that are in development. Although not an exhaustive list of technologies, this is a "snapshot" of leading technologies and activity in this space. It is intended to act as a guide to the key processes and technology platforms. There have also been developments in hybrid technologies that combine an additive process described in Table 1 with traditional manufacturing technologies such as Computer Numerically Controlled (CNC) machining.

Classification	Material	Process description	Example Commercial systems	Example Developmental system
Powder Bed Fusion	Metal	**Selective Laser Melting (SLM)** **Electron Beam Melting (EBM)**	EOS (Germany) Concept Laser (Germany) Renishaw (UK) Realizer (Germany) SLM Solutions (Germany) Matsuura (Japan) ARCAM (Sweden)	
	Polymer	**Selective Laser Sintering (SLS)** **Masked Sintering** **Infrared Sintering**	EOS (Germany) 3D Systems (USA) Blue Printer (Denmark) HP (USA)	Norge (UK) Sharebot (Italy) FIT (Germany) Renishaw / DMU (UK) University of Sheffield (UK)
	Ceramic	**Laser Sintering**	EOS (Germany)	
Directed Energy Deposition	Metal (Powder feed)	**Laser Metal Deposition (LMD)** **Plasma Deposition**	Trumpf (Germany) Optomec (USA) Accufusion (Canada) Irepa Laser (France) Hybrid Manufacturing Technologies (UK)	Honeywell (USA)
	Metal (Wire feed)	**Electron Beam Direct Melting** **Wire Arc**	Sciaky (USA)	Cranfield University (UK)
Material Jetting	Photo-polymer	**Photopolymer Ink-Jetting**	Stratays (USA) 3D Systems (USA) LUXeXcel (Netherlands)	
	Wax	**Wax Ink-Jetting**	3D Systems (USA) Solidscape-Stratasys (USA)	
	Organic	**Organic Ink-Jetting**		Wake Forest Institute for Regenerative Medicine (USA)
	Metal	**Liquid Metal Jetting**		University of Nottingham (UK)
Binder Jetting	Metal	**Metallic Binder Jetting**	ExOne (USA)	
	Polymer	**Polymer Binder Jetting**	Voxel Jet (Germany)	
	Ceramic	**Gypsum Binder Jetting** **Ceramic Binder Jetting** **Sand Binder Jetting**	3D Systems (Z-Corp) Therics (USA) ExOne (USA)	
Material Extrusion	Polymer	**Extrusion** **Co-Extrusion**	Stratasys (USA) MakerBot (USA) Delta Microfactory (China) 3D Systems (USA) Markforged	
	Ceramic	**Extrusion** **Paste Extrusion**		MIT (USA) Loughborough (UK)
	Organic	**Extrusion**	3D Systems (USA) Organovo (USA)	
VAT Photopolymer-isation	Photo-polymer	**Stereolithography (SLA)** **Digital Light Processing (DLP)** **Two Photon Lithography (2PL)**	3D Systems (USA) Formlabs (USA) Envisiontec (Germany) Asiga (USA) Carbon 3D (USA) Nanoscribe (Germany)	Peachy Printer (Canada)
	Photopolymer (ceramic)	**Ceramic Loaded Stereolithography**	Lithoz (Austria) 3DCeram (France)	
Sheet Lamination	Metallic	**Ultrasonic Consolidation**	Fabrisonic / Solidica (USA)	
	Ceramic	**Laminated Objet Manufacture**	CAMLEM (USA)	
	Organic	**Adhesive Lamination**	MCor (Ireland)	

Table 1 (NB: This is not an exhaustive list of AM technologies that have been commercialised or in development. It is intended to act as a guide to the key processes and technology platforms.)

Why is additive manufacturing important to the UK economy?

Over the last 30 years, additive manufacturing has become an underpinning technology of high value manufacturing. The UK has been a world-leader in developing this technology and has also pioneered applications for its commercialisation.

The additive manufacturing industry, including machine and material sales as well as associated services was valued at $3.07 billion in 2013 and predicted to grow to $21 billion by 2020 (Wohlers Report 2014[3]). This will be realised through increased applications for the technology, as well as machine and material sales, associated services, training and research.

The UK has a strong presence in the high value manufacturing economy and there is clear potential for opportunity creation by exploiting additive manufacturing in key sectors, such as aerospace, medical devices and implants, power generation, automotive and the creative industries. There are also opportunities for companies to engage in the manufacture of additive manufacturing systems for sale to both domestic and international markets.

Understanding Additive Manufacturing within the UK

Background to this report

In September 2012, Innovate UK (formerly the Technology Strategy Board) published the report *"Shaping our National Competency in Additive Manufacturing"* which presented a definitive view of the state of additive manufacturing research within the UK[1]. The report was produced by the Additive Manufacturing Special Interest Group (SIG) lead by the Materials Knowledge Transfer Network (KTN) working with the Aerospace & Defence KTN (now combined into the single Knowledge Transfer Network) and supported by a wide cross section of the UK's academic and industrial additive manufacturing community. The SIG 2012 report considered the opportunities and barriers for adoption of additive manufacturing within the UK, and what actions needed to take place to address these.

As part of the SIG 2012 report, an analysis was undertaken to identify the Strengths, Weaknesses, Opportunities and Threats to the UK's additive manufacturing position and its ability to lead in the development of additive manufacturing. This concluded that the UK had a well-established and equipped additive manufacturing research community and that it was a world-leading source of additive manufacturing related knowledge and activity. It also highlighted that the technology had been recognised as being of strategic importance by various funding bodies, which would be key to supporting the development of fundamental research and future innovations. However, the report identified a number of weaknesses in the UK's position, including:

- There was a limited (albeit inquisitive) number of industrial supporters and a general lack of appreciation and understanding of the benefits of additive manufacturing within industry. The UK was not doing enough to engage with the broader user community.
- There were missing links in the supply chain, with low engagement from organisations in aligned technologies (such as optics, software and jetting).
- There was low commercial exploitation of technology innovation, with no world-leading equipment manufacturers in the UK.
- The sector was highly fragmented with little strategic direction for the additive manufacturing community, and different sectors and supply chain members had conflicting end goals.

The report recommended three key actions to strengthen the UK's position in additive manufacturing and drive forward the UK additive manufacturing research and commercialisation agenda. These were to:

1. Develop new machine platforms based on the UK's strong research capability in photonics, process control, materials science, ink jet technologies and software development.
2. Consolidate UK research excellence and incentivise commercial exploitation of promising technology, accelerating development programs along the TRL range beyond 6.
3. Stimulate the development and exploitation of new business models enabled by additive manufacturing co-ordinating supply chain elements to grow a sustainable competitive advantage for the UK.

Underpinning these recommendations was an emphasis on the need to define a clear implementation strategy, led by industry. To this end, the SIG 2012 report recommended the establishment of a formal network of additive manufacturing developers and users, with a common vision and a common voice. It also called for the implementation of industrial policies to encourage and strengthen the growth of the additive manufacturing supply chain.

The recommendations of the SIG 2012 report were also supported by the "*Foresight: The Future of Manufacturing"* report published by the Government Office for Science in 2013[4] which noted that many new manufacturing technologies, including additive manufacturing do not seem to have a joined up approach as to how they can be best exploited to the benefit of the UK economy. This report concluded that government needed to take a more targeted approach to supporting manufacturers and develop strategic approaches that facilitate the emergence of challenger businesses. The Foresight report emphasised the need to support new business models that cut across manufacturing technologies and to enable collaboration between sub-sectors.

Aims of this report

The objective of this *Mapping UK Research and Innovation in Additive Manufacturing* report is to follow up on the SIG 2012 report by mapping the current state of additive manufacturing research in the UK and understanding how the research landscape has changed since its publication. This report reviews where investment has been made in additive manufacturing, identifying what the key areas of research interest are for the UK and building a picture of the UK's research capabilities. In doing so, the report aims to understand if the opportunities and barriers identified in 2012 have been addressed. By analysing the research projects that have been undertaken since 2012, this *Mapping UK Research and Innovation in Additive Manufacturing* report identifies where the profile of research activity has changed within the UK, what shifts have taken place within the primary research actors and institutions and the industry sectors engaged in research, where the UK is strongest in additive manufacturing research and where there are current or emerging gaps in the research base.

Methodology

This study evaluates the UK's involvement in additive manufacturing research since the SIG 2012 report was published. In order to qualify for inclusion in this analysis, projects had to meet all of the following criteria:

- 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.

NB: It should be noted that simply using existing and commercialised additive manufacturing technologies in order to carry out research in other fields was not considered to be actively contributing to the advancement of the industry and so was not included in the analysis. For example, a biological research project that evaluates the effectiveness of catalysts within microfluidic devices where an additive manufacturing technology is used to produce the micro-fluidic device housing or reactor would not be considered to be advancing the field of additive manufacturing and so would not be included in this analysis.

How was the data collected?

The data set used in this analysis was developed by evaluating and collating publicly available information and then supporting this with direct engagement with research institutions. Public databases of research investment such as the European Union's Cordis database and the UK's Gateway to Research database were first used to build a list of UK projects; this was then augmented with direct contact with Innovate UK and the EPSRC. This 'first pass' of projects was then built upon by interviewing relevant research organisations to develop a detailed picture of both research activities and inter-relationships between industry and the UK science base. Requests for additional data were made to 40 research organisations known to engage in additive manufacturing activity, of which 20 provided bespoke information for this study, with the remaining 20 organisations being reviewed based on their public domain profiles.

What data was obtained?

For each research project that was identified, data relating to a variety of aspects of the project was collected, including:

- The scope of the research project. Example project scopes included: the development of existing additive manufacturing technologies; the innovation of new additive manufacturing technologies; the investigation of technologies that enable additive manufacturing production, such as materials or software; the design of new products using additive manufacturing technologies.
- The type of additive manufacturing technology platform being researched and the material class of interest.
- Which industry sectors the project focusses on, such as the aerospace, automotive or medical sectors. Where no clear industry focus had been identified due to the low maturity of the technology, the research was categorised as high-value manufacturing.
- The value and source(s) of funding for the project.
- Which organisations are involved as project partners, including the type of organisation (such as commercial or academic) and their industry sector.
- The percentage of the project directly related to additive manufacturing technologies. Many projects that were identified included elements of additive manufacturing research within the context of other research activity. To minimise the risk of including the funding for these other research activities in the analysis, a percentage was assigned to each project based on the proportion of time allocated to additive manufacturing research or the number of research outcomes related to additive manufacturing.
- The percentage of the project related to the UK. Where projects involved research partners from outside of the UK, a ratio was calculated of UK partners to non-UK partners.
- The technology readiness level (TRL) of the research. TRL scales enable an assessment of the commercial maturity of the technology at the start and end of a project, demonstrating how much progress has been made on developing the technology to bring it to market.

Results and Analysis

Key findings

The analysis within this report shows that additive manufacturing research funding has continued to grow from the £15 million committed in 2012 to almost £30 million spent on research in 2014. Moreover, by February 2015, some £25 million of funding had already been committed to projects taking place this calendar year.

This funding has been attributed to 244 research projects, a significant growth in comparison to the SIG 2012 report which identified 136 projects. A similar trend is seen when looking at the number of organisations involved in research projects; the SIG 2012 report identified a total of 81 organisations involved in research projects – in 2015 this has grown to 243 organisations. Most of this growth has come from greater engagement within commercial organisations. In 2012, there were 57 commercial organisations involved in additive manufacturing research - a figure which has now grown to 165 commercial organisations. There has also been an increase in the number of academic institutions engaging in research, with 24 universities identified in 2012, compared to 41 universities in 2015.

In summary, between 2012 and 2014/15, there has been a:

- 100% increase in annual additive manufacturing R&D expenditure (2012 – 2014)
- 80% increase in the number of active R&D projects
- 200% increase in the number of industrial organisations engaged in additive manufacturing research
- 71% growth in the science base engaged in additive manufacturing research

Figure 1 shows the profile of research and development expenditure within the UK since 2007. As it can be seen, there was a dip in funding in 2012 and 2013, largely resulting from the end of Regional Development Agency (RDA) and European Regional Development Fund (ERDF) funded initiatives. However, this dip has now been offset by an increase in investment from other bodies such as Innovate UK and the EPSRC, with the 2014 expenditure figure in line with the growth trajectory of the 2008 to 2011 period. It should be noted that although funding appears to decrease over the time period 2015 to 2022, this is because very little funding has so far been allocated or declared for these years. The values for this time period will inevitably increase as new funding is made available.

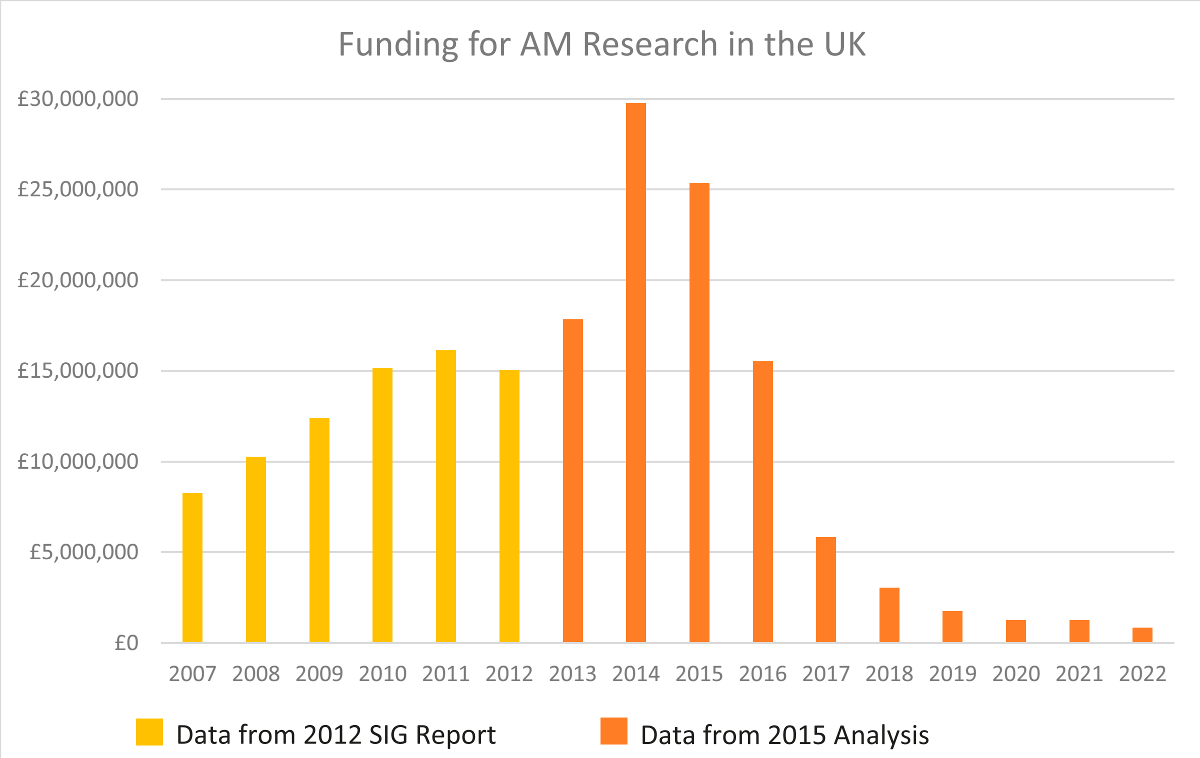

Figure 1

In terms of research focus, the area receiving the greatest focus and expenditure is metallic additive manufacturing technologies. This remains unchanged from the 2012 SIG report. This is being driven by interest from the industrial and aerospace sector, although sectors including automotive and defence appear to have reduced their research spend in the area since 2012. Investigation within these sectors suggests that this may be a function of early stage research failing to identify suitable additive manufacturing technologies for these sectors' specific needs, namely the very high level of repeatability needed in the defence sector not being achievable using additive manufacturing or the piece part economics of the automotive sector being largely unattainable using additive manufacturing.

It is interesting to note that industrial funding is predominantly driving projects with a low technology readiness level and a lower technology readiness level than in the 2012 study. This may be due to a realisation that current technology platforms are not suited to a wide spread of potential industrial applications and as such future users are driving the research agenda down the TRL scale to focus more on the underlying science. In short, companies may have realised that current rapid prototyping platforms are not suited to Industrial manufacturing applications and fundamental changes must be made at a core-technology level to drive future adoption.

What research is being carried out in the UK?

Application areas of the research

The research that is being carried out within the UK spans a wide range of application sectors from defence to consumer products, from automotive to the creative industries. The single largest application category is Enabling Technologies (Figure 2), which is comprised not only of research projects looking at the commercialisation of additive manufacturing technology within the manufacturing industry, but also projects where there is no identified application yet for the research due to its low technology readiness level. As such, almost £47 million has been allocated to Enabling Technology projects, accounting for 40% of research carried out in the UK. Examples of the type of research project that fall into this category include *INSIDE-OUT: Statistical methods for Computed Tomography validation of complex structures in Additive Layer Manufacturing* or the *ARMoR* project to develop a novel manufacturing platform. The Enabling Technology category also includes research into post-processing activity such as the Innovate UK-funded *TICLE* to develop titanium cleaning methods for implants and a number of projects looking at improving the surface finish of components. Other major research areas include aerospace and medical, each receiving approximately £16 million of funding.

It should be noted that for projects with a focus on multiple application sectors, the project value was split equally between the sectors.

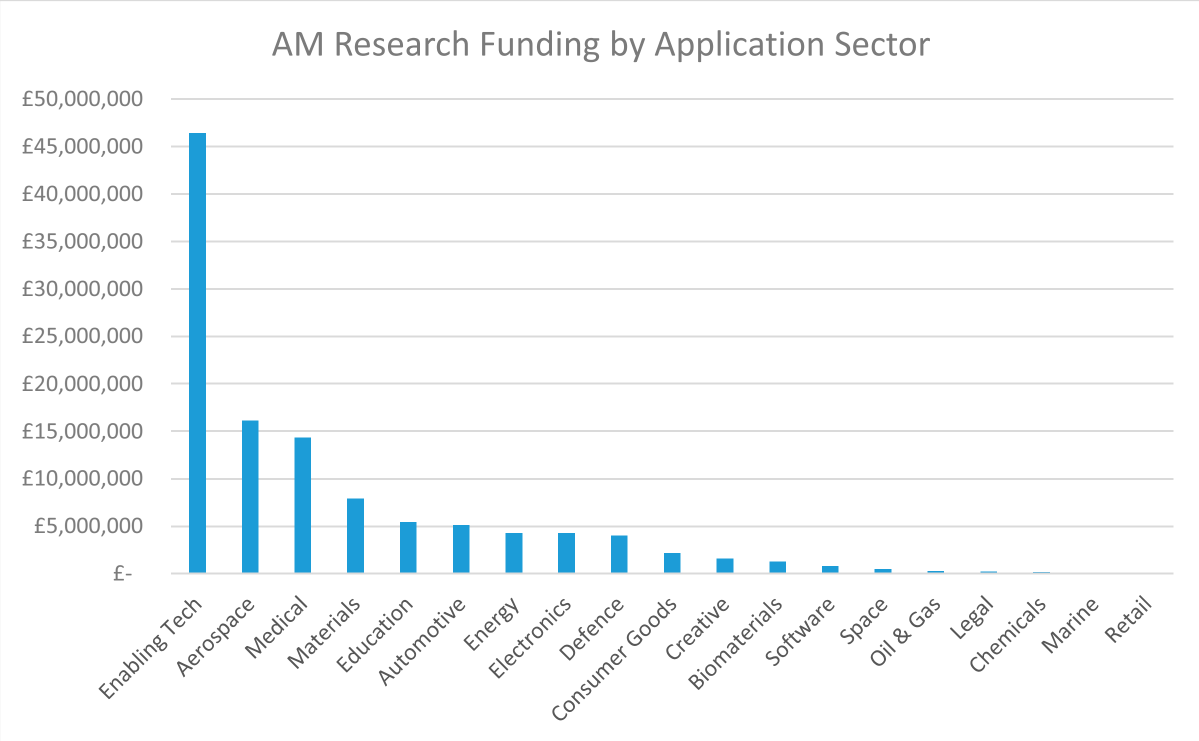

Figure 2

Types of additive manufacturing research funded

As it can be seen in Figure 3, the majority of research that is undertaken in the UK is in the form of academic and industrial collaborative projects, with 53% of funding allocated for projects of this type. This category includes projects such as the EPSRC-funded *HiDepAM: High Deposition Rate Additive Manufacture of Complex Metal Parts* or the FP7-funded *NEXTFACTORY* that involve industrial organisations, either individual or in consortium, in collaboration with academic institutions. Over £16.5 million has also been allocated to additive manufacturing research to develop research centres such as the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing and for capital equipment grants relating to additive manufacturing technology.

There has been a similar amount of funding allocated to supporting PhDs with an additive manufacturing focus; with over £10 million of the funding to the EPSRC Centre for Doctoral Training in additive manufacturing, split between Nottingham, Newcastle, Liverpool and Loughborough Universities. Research that is carried out solely by academic institutions has attracted £10.6 million, while funding for research carried out solely by industrial organisations has attracted £8.6 million.

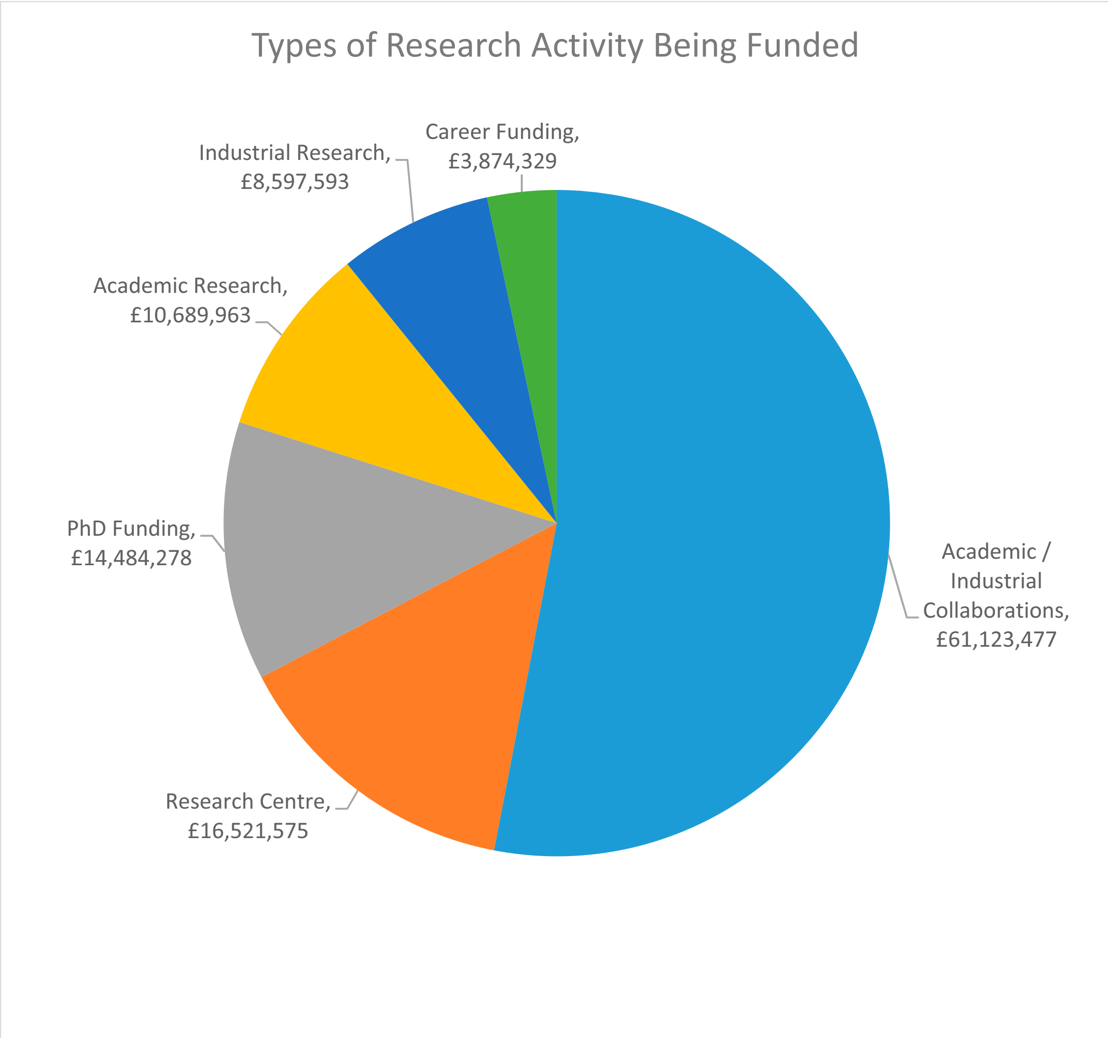

Figure 3

Research focus within the additive manufacturing ecosystem

Within the background research supporting this report the authors considered each project in terms of the purpose of the research and the project's objectives. The following definitions were used to segment the research activity.

Enabling Technology	This category included projects that enable the development of additive manufacturing technology, such as material characterisation and software tools.
Process Innovation	This category included projects that were developing novel forms of additive manufacturing technology.
Process Development	This category included projects that were developing existing forms of additive manufacturing technology, to raise their technology readiness level.
Process Validation	This category included projects that were validating additive manufacturing technology for use in commercial applications.
Product Development	This category includes the development and optimisation of products for manufacture using additive manufacturing technology.

Table 2 – Research Focus Definition

Using the definition described in Table 2, the single largest category of research is Enabling Technology, with 41% of research having a focus on developing the underpinning science of additive manufacturing. This is a significant shift from the 2012 SIG report where enabling science accounted for less than 25% of all investment. The shift is however largely as a result of the increased focus in the technology area by funding bodies such as the EPSRC who have funded dedicated centres such as the EPSRC Centre for Innovative Manufacturing in additive manufacturing along with a host of other low-TRL projects at other academic institutions.

Within the 'enabling' category, *materials* was the single largest research focal area, with over £17 million of funding spent on the development and optimisation of new materials for use with additive manufacturing technologies. Examples of projects with a high materials focus include ACCMET – an FP7 project to investigate new alloy formulations through direct laser deposition – and an Engineering Fellowship for Growth grant for the development of polar materials for additive manufacturing.

Significant funding has also been allocated to projects with a product design focus. In these projects there is an increased level of near to market industrial activity, where industrial partners are using collaborative research funding to assist in the development of business cases for additive manufacturing adoption.

With regard to the development of novel additive manufacturing processes through research projects, technologies that enable multi-material production have received the largest amount of funding. This is primarily due to the focus of the EPSRC Centre for Innovative Manufacturing in Additive Manufacturing on developing new multi-material technologies. Other significant projects with a multi-material focus include the *Direct Digital Fabrication* project involving the universities of Loughborough, Warwick, Heriot-Watt and Sheffield.

Additive manufacturing technology focus within research

The UK research community is involved in evaluating almost all types of additive manufacturing technology, however analysis suggests significantly more activity is taking place in metals technology than in polymers. However, the bias towards metals has reduced since the 2012 SIG report, which showed some 80% of all projects focused on metallic technologies. Discounting 'mixed material' research projects and focusing on only metallic, polymeric and multimaterial research, discrete metallic now only accounts for some 66% of research activity.

Where possible, the type of additive manufacturing process involved in each research project has been identified (Figure 4) Of the metallic processes, with a total research spend of almost £40 million there is still some four times more investment than polymeric processes. The authors believe that this is largely due to the cost and complexity of validating materials and components into the high adoption sectors, such as aerospace. Where multiple technologies were studied within the same project or where it was not possible to identify the additive manufacturing technology involved, the process type was classified as "various" – this category accounts for approximately 47% of all additive manufacturing funding within the UK.

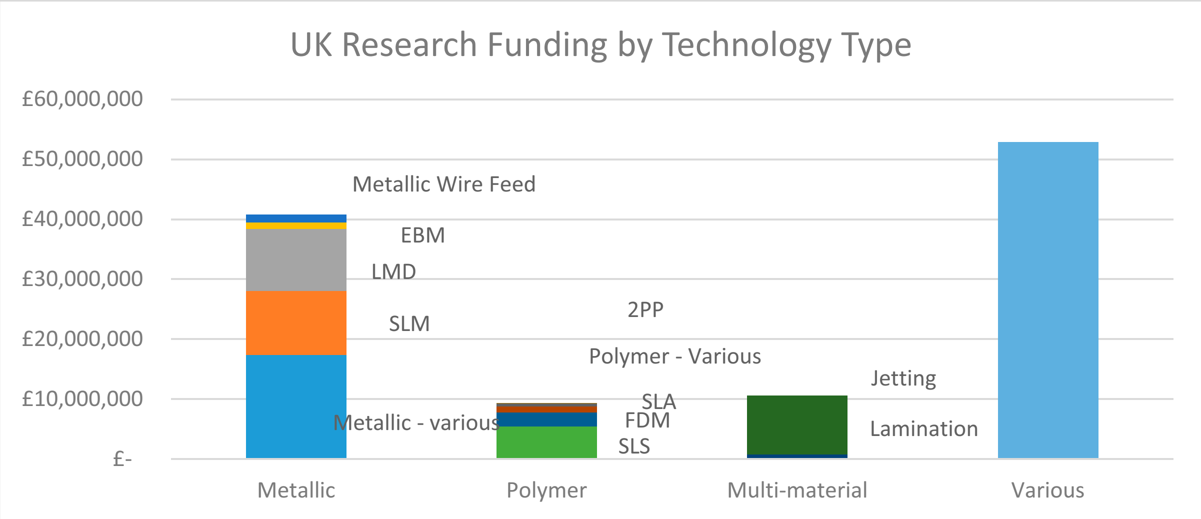

Figure 4

By comparing project application sectors to additive manufacturing technology types, it is evident that research into metallic additive manufacturing technology is most predominant in projects with a research focus on the aerospace and enabling technology. Projects within this category include ALMER, an Innovate UK project led by Rolls-Royce plc which focuses on reducing aircraft emissions through optimisation of metallic components, and DARE, an EPSRC project led by the University of Sheffield investigating new alloys for additive manufacturing technologies. By contrast, there is very little aerospace-related research into polymer technology; the industry with the largest amount of research into polymer technology is the medical sector which includes projects such as A-FOOTPRINT, a Framework 7 Project looking at the development of customised orthotics using polymeric additive manufacturing technologies. Interestingly, within the commercial domain, materials such as flame retardant laser sintered nylon powders and aerospace approved ULTEM thermoplastic are being progressively used by aerospace manufacturers. This would suggest that in many cases polymeric additive manufacturing processes may now be beyond the technology readiness level of collaborative projects.

This distribution of projects by both industry vertical and technology class can be seen detailed in the heat map in Figure 5. This chart shows that the single largest technology funding area is for "various" – a category which covers projects where the research is applicable to multiple additive manufacturing platforms. For example, this category includes projects such as the development of software or post-processing methodologies this research is applicable to a variety of additive manufacturing processes.

	Various	Metallic - various	Selective Laser Melting	Jetting	Laser Metal Deposition	Selective Laser Sintering	Fused Deposition Modelling	Metallic Wire Feed	Electron Beam Melting	Stereo-lithography	Lamination	Polymer - Various	2 Photon Polymerisation	Grand Total
Enabling tech	£32,044,278	£4,940,842	£1,331,523		£4,998,752	£1,342,587		£33,224	£760,943		£351,833	£388,970		£46,192,954
Aerospace	£4,891,775	£4,661,871	£2,877,552	£125,000	£1,516,122	£480,709		£1,260,242				£12,500	£37,275	£15,863,046
Medical	£5,881,127	£583,644	£2,732,908	£2,648,347		£1,066,447	£844,273		£268,272	£677,000				£14,702,019
Materials	£682,691	£1,341,082	£29,900	£2,517,021	£2,165,033	£965,085						£120,000		£7,820,812
Education	£5,297,018		£89,612											£5,386,629
Automotive	£448,867	£1,807,641	£2,574,348	£49,546		£33,051								£4,913,452
Electronics	£2,513,326	£99,505	£263,232	£1,215,188							£351,833			£4,443,085
Energy	£777,708	£2,400,065	£657,170		£184,000									£4,018,944
Defence	£2,003,312	£100,000	£30,000	£1,705,282	£60,000		£36,362						£37,275	£3,972,230
Consumer Goods	£1,527,056					£699,996								£2,227,051
Creative	£852,874					£172,430	£545,132							£1,570,435
Biomaterials	£93,000			£1,042,199						£309,763				£1,444,962
Software	£430,360			£350,000										£780,360
Space						£480,709								£480,709
Oil & Gas					£300,000									£300,000
Legal	£203,057													£203,057
Chemicals				£151,736										£151,736
Marine	£70,000													£70,000
Retail	£33,000													£33,000
Grand Total	£57,749,448	£15,934,652	£10,586,246	£9,804,318	£9,223,908	£5,241,014	£1,425,767	£1,293,466	£1,029,216	£986,763	£703,666	£521,470	£74,549	**£114,574,483**

Figure 5

Technology readiness of additive manufacturing research in the UK

Technology readiness level (TRL) scales are widely used in research communities to assess the maturity of technology and indicate how close it is to full implementation or commercialisation. On this scale, a project at TRL1 means that basic principals have been observed, while a technology at TRL9 has been fully qualified and is at the point of commercialisation. It should be noted, however, that this is a relatively subjective scale, especially when TRLs have been provided by a large number of sources from a variety of industries, and results should be treated as indicative.

Assessing the TRLs of each of the UK's additive manufacturing research projects shows that there is a wide range in the maturity of additive manufacturing within sectors. Figure 6 indicates that the medical sector has a relatively low average TRL but individual projects within that sector span a wide range, from very early stage projects at TRL1 to commercially ready technology at TRL9. This should come as no surprise, given that some medical devices such as hearing aids have been manufactured using additive manufacturing for over a decade. Similarly, a significant body of research into applications such as orthopaedic implants, prosthetics and orthotics have led to a number of commercial product offerings. When compared to the 2012 SIG data, it is found that the average TRL of medical projects has increased from TRL3 to TRL4. However, some companies within the sector remain new to additive manufacturing technology altogether and as such are accelerating their own adoption through collaborative research activity. It is also interesting to see that the sectors making the most significant investment, namely aerospace and "Enabling Technologies" still have relatively low TRLs, albeit again, the average TRL within these sectors has increased by at least one or two points on the TRL scale.

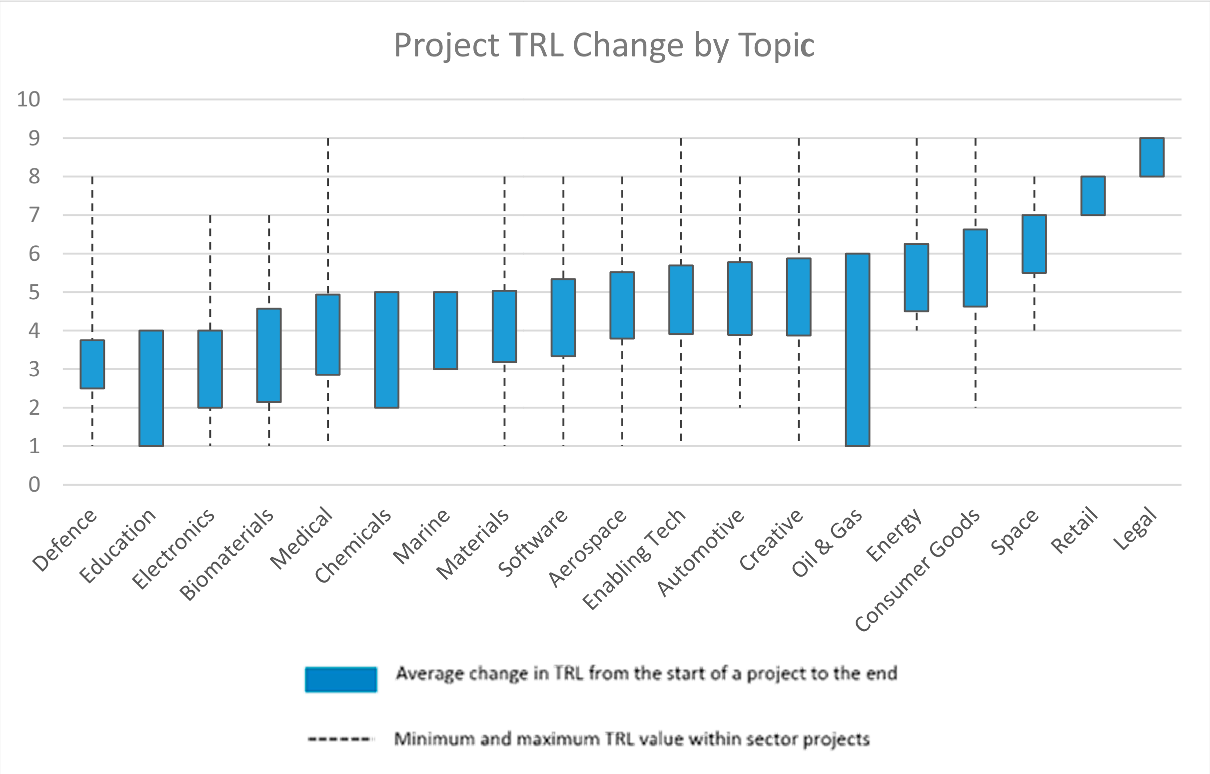

Figure 6

When comparing the TRL change with regard to additive manufacturing technology type (Figure 7), it is apparent that well-established technologies such as selective laser sintering (SLS), selective laser melting (SLM) and electron beam melting (EBM) are the most mature. Emerging technologies such as two photon polymerisation (2PP) have a much lower TRL as this is still very much limited to lab research. It is interesting to note that jetting research has a very low average TRL; although jetting processes have been around for many years and have been extensively commercialised through systems such as the Stratasys Polyjet and Solidscape wax technologies, there is now a wide range of early stage research focussing on the jetting of more exotic materials such as metals and biomaterials. This could be used as an early stage indicator for the platform architecture of the future, where jetting is seen as both a cost effective and scalable methodology for depositing multiple materials digitally.

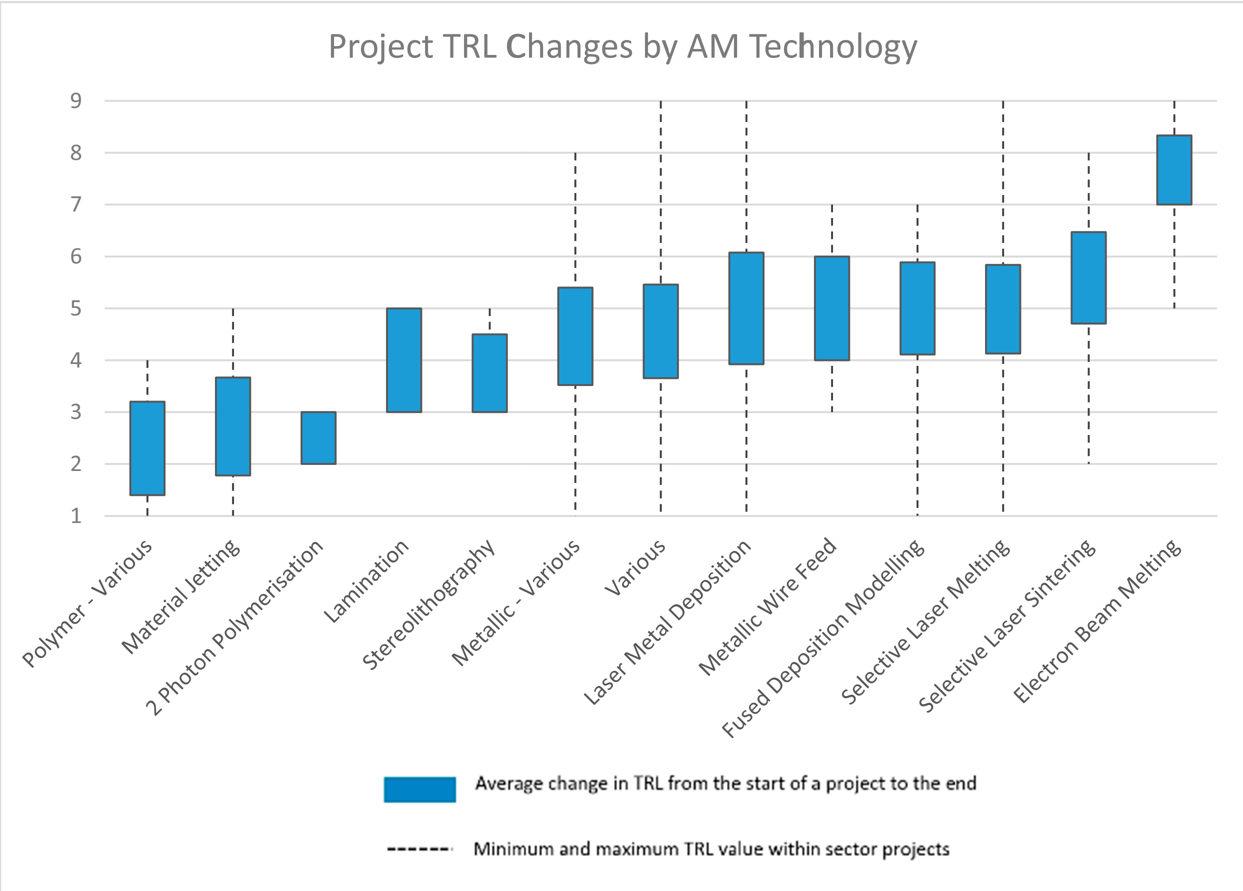

Figure 7

Who is carrying out additive manufacturing research in the UK?

Organisations involved in research

There are 245 organisations that have been identified as a named partners within additive manufacturing research projects in the UK during the period of this study; the distribution of funding between these partners forms a long tail distribution, with a very small number of organisations receiving a high proportion of funding. As seen in Figure 8, 38% of funding has been received by three organisations – University of Nottingham, University of Sheffield and Loughborough University; the distribution of funding then tails off over the remaining 242 organisations. Excluding the top 3 organisations, the average amount of funding per organisation since 2012 is £289,188.

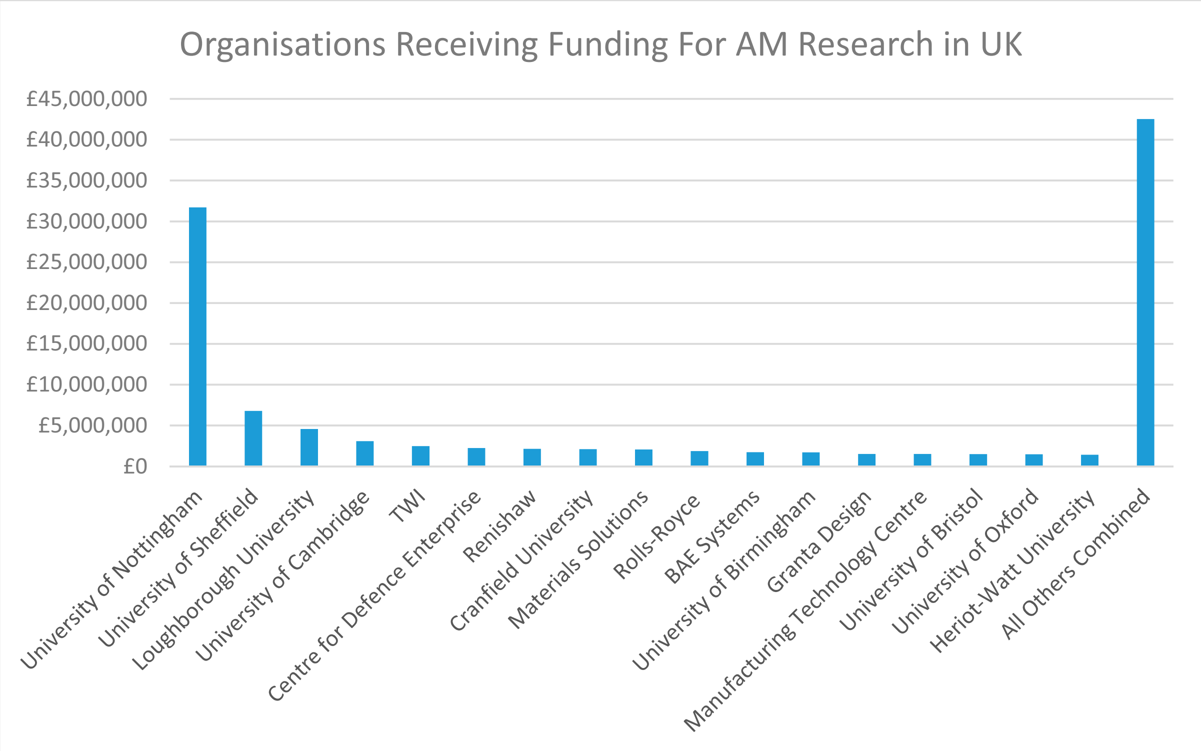

Figure 8

Due to the difficulties in obtaining information relating to internal R&D spend within commercial organisations, this study has focussed on identifying the distribution of public funding from sources such as Innovate UK and the European Union's FP7 programme, as well as the investment of funding from private sources into research organisations such as universities. As a result of this methodology, commercial organisations in Figure 8 appear to have a smaller R&D budget than is actually the case.

As an alternative to assessing the funding received by organisations for additive manufacturing research, one metric of company engagement and therefore 'enthusiasm' for additive manufacturing research is to look at the number of projects that each organisation is involved in and the number of unique partners within each organisation's research network; this has been mapped in Figures 9 and 10. As it can be seen in both of these charts, there are a number of organisations that are heavily involved in research projects, such as Renishaw and BAE Systems who are part of extensive research networks, along with the universities of Nottingham, Loughborough & Sheffield and research organisation such as TWI and the MTC. These critical masses of research build knowledge and skills in specific areas, however it should be noted that there are no formal networks between these organisations beyond the links created by individual projects.

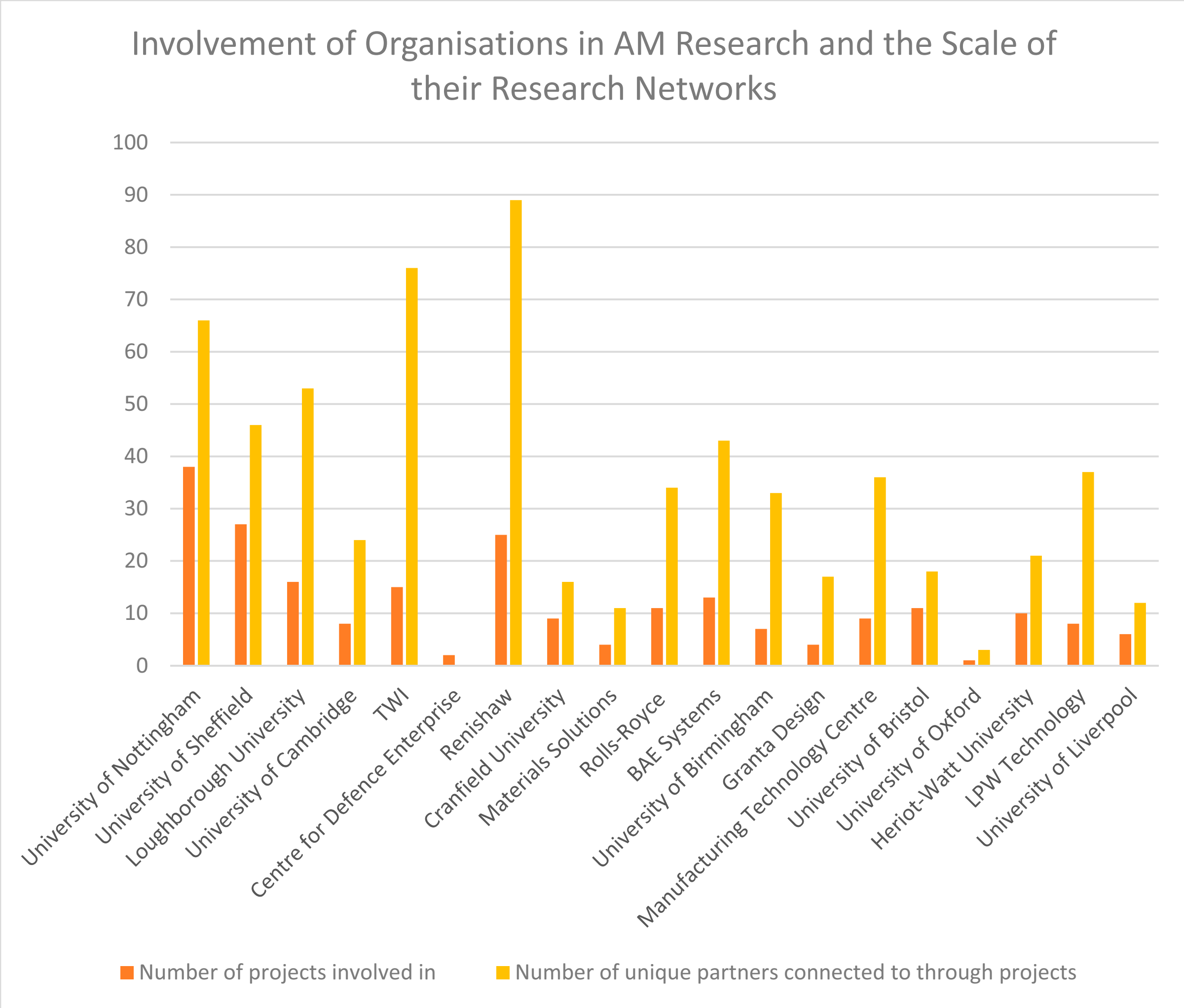
Involvement of Organisations in AM Research and the Scale of their Research Networks
100
90
80
70
60
50
40
30
20
10
0
University of Nottingham
University of Sheffield
Loughborough University
University of Cambridge
TWI
Centre for Defence Enterprise
Renishaw
Cranfield University
Materials Solutions
Rolls-Royce
BAE Systems
University of Birmingham
Granta Design
Manufacturing Technology Centre
University of Bristol
University of Oxford
Heriot-Watt University
LPW Technology
University of Liverpool
Number of projects involved in
Number of unique partners connected to through projects

Figure 9

Research Networks Created Through Projects (for the 10 most connected organisations)

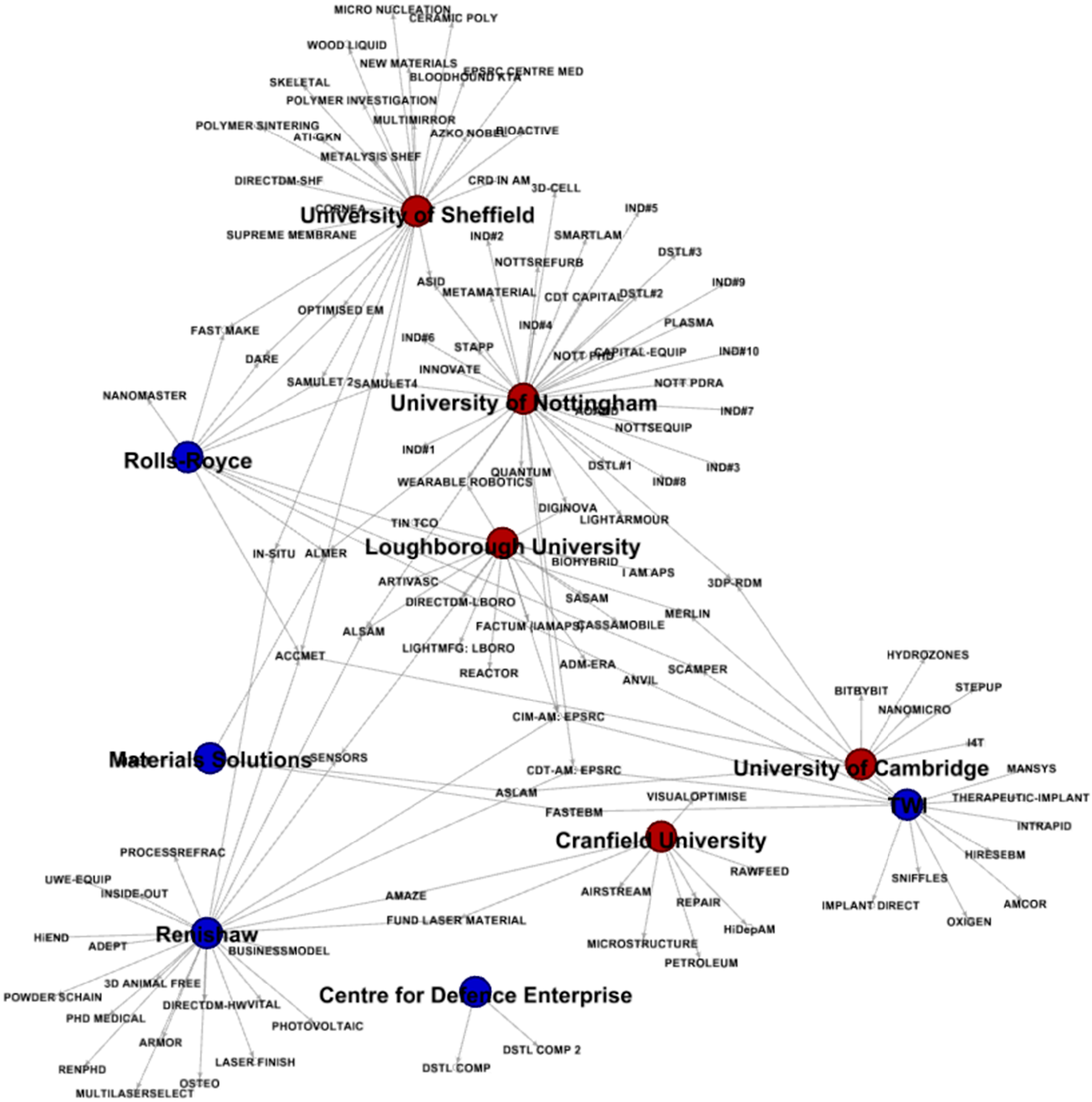

Figure 10

Geographical distribution of academic research

As seen in Figure 11, it is universities within the East Midlands and South Yorkshire such as the University of Nottingham, Loughborough & the University of Sheffield that are receiving the most significant sums of funding. This is largely a legacy of the very early stage research activity in the mid 1990's led by Professor Phill Dickens, which can be directly linked to academics now operating at Nottingham, Loughborough, Sheffield & Birmingham Universities along with research staff within TWI Sheffield and the MTC in Ansty.

The 2012 SIG Report identified a critical mass of UK additive manufacturing research being located in the East and West Midlands and Southern Yorkshire. This is still observed, as shown in Figure 11, although more significant pockets are now emerging around Cambridge, London and the South West.

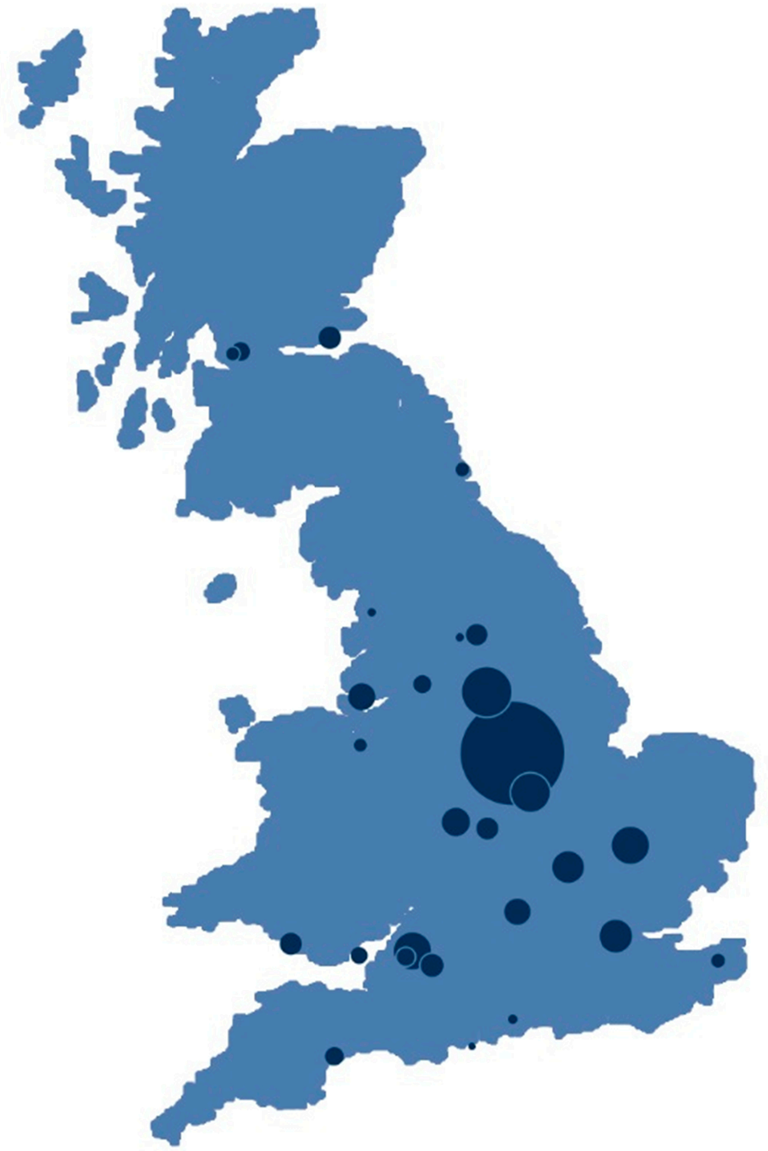

Figure 11

Industries of commercial partners

Commercial partners within additive manufacturing research projects represent a wide range of industries, with Industrial and High-Value Manufacturing companies being the most numerous as seen in Figure 12. Additive manufacturing and Materials companies also naturally have a high involvement in research projects, as would be expected. Since the 2012 SIG report, there has been an increase in other sectors engaging in additive manufacturing research including the electronics and energy sectors along with the creative and retail sectors. It is interesting to note the involvement of project partners from service industries such as Telecommunications, Professional Services and Education, which is indicative of the spread of additive manufacturing and 3D printing within society and the commercial value chain as a whole.

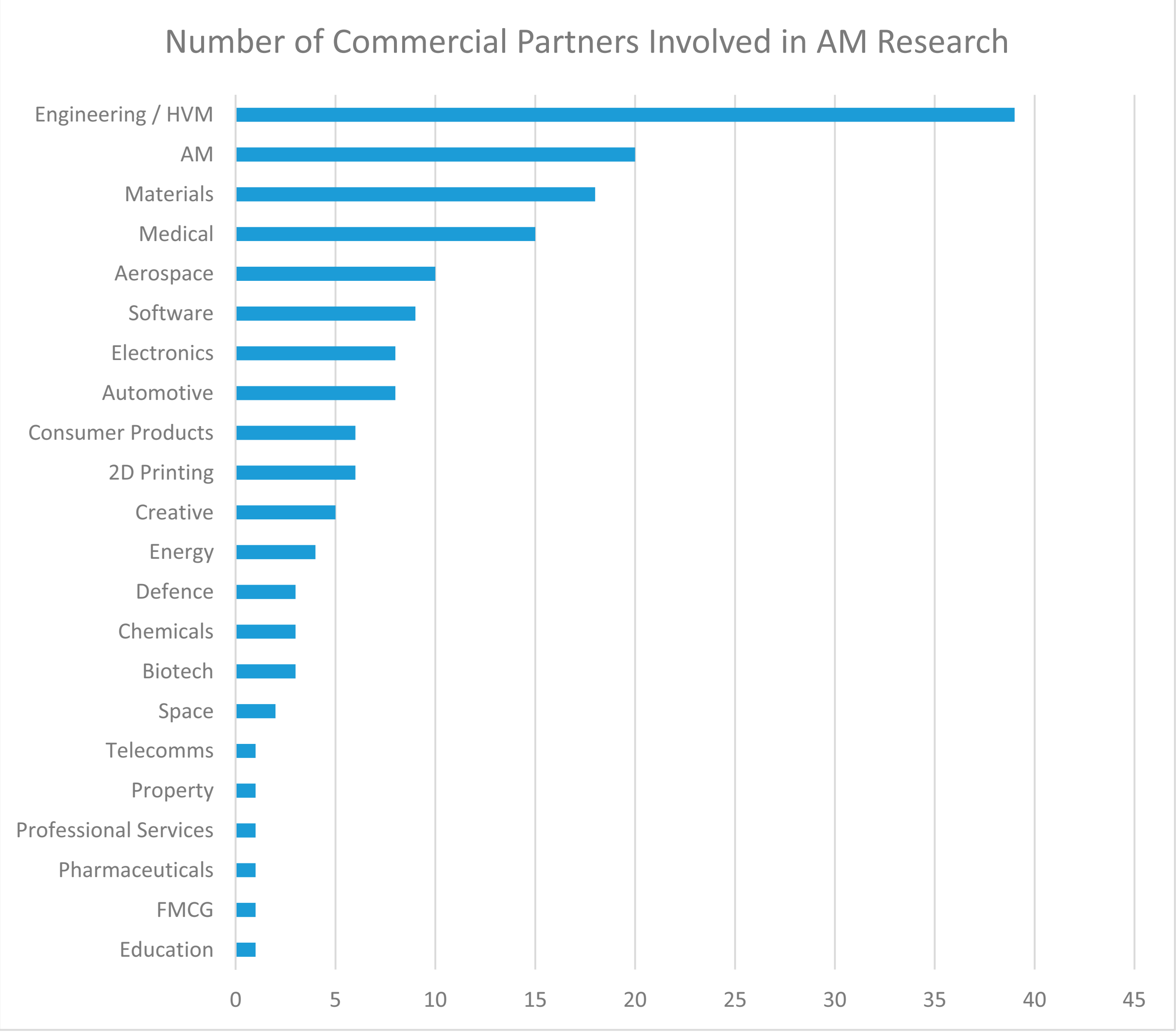

Figure 12

How is additive manufacturing research within the UK being funded?

A total of £115m has already been invested or committed to UK additive manufacturing research during the period September 2012 to September 2022. This includes academic and industrial collaborations, PhD projects and core funding to research centres. As seen in Figure 13, approximately 50% of this funding has been provided by the EPSRC and industrial contributions. This is in comparison to the 2012 SIG research where only £14m of £96m came from the EPSRC and some £25m of the £96m came from industry. It was identified in this report that “based on current funding commitments, the research community will become largely supported by [non-Innovate UK] funding sources, such as the EU’s Framework Programme by the end of 2012”. It would appear that this is partially true, as funding from EPSRC and Industrial sources now play such a significant role in additive manufacturing research.

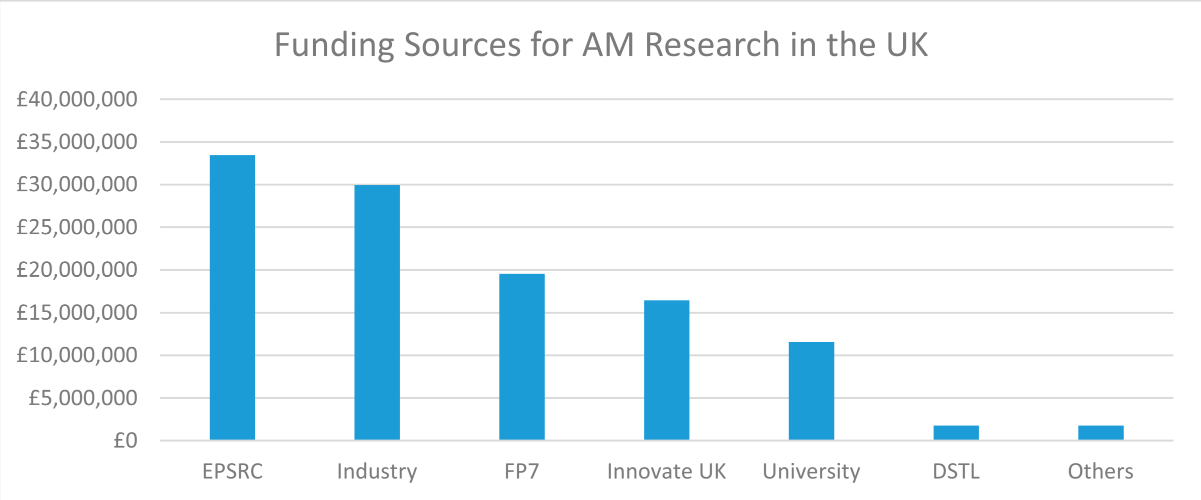

Figure 13

By considering the types of hardware being invested in by the different funding bodies and funding sources, it can be seen from Figure 14 that Framework 7 Programmes have invested the most heavily in metals technology while the EPSRC is contributing heavily to research into jetting technologies. There is very little investment from universities directly in metals technologies, suggesting the platforms used by universities are largely there for demonstration and technology transfer purposes.

	Various	Metallic - various	Selective Laser Melting	Jetting	Laser Metal Deposition	Selective Laser Sintering	Fused Deposition Modelling	Metallic Wire Feed	Electron Beam Melting	Stereo-lithography	Lamination	Polymer - Various	2 Photon Polymerisation	Grand Total
EPSRC	£21,696,696	£1,813,399	£2,258,092	£5,633,222	£558,909	£468,556	£583,421					£462,261		£33,474,557
Industry	£13,262,485	£5,075,614	£3,443,351	£2,416,155	£3,137,092	£1,521,691	£52,267	£638,427	£200,161	£58,076	£158,601			£29,963,919
FP7	£3,961,701	£6,839,988	£452,109	£1,002,024	£3,970,192	£1,726,397			£829,055	£251,688	£545,065			£19,578,218
Innovate UK	£6,827,845	£2,057,650	£3,762,562		£1,345,933	£1,188,314	£608,931	£655,039						£16,446,275
University	£9,724,112	£148,000	£448,132	£563,349	£127,782	£336,056	£144,786					£59,209		£11,551,426
DSTL	£1,550,064			£189,568			£36,362							£1,775,994
Others	£726,545		£222,000		£84,000					£677,000			£74,549	£1,784,094
	£57,749,448	£15,934,652	£10,586,246	£9,804,318	£9,223,908	£5,241,014	£1,425,767	£1,293,466	£1,029,216	£986,763	£703,666	£521,470	£74,549	**£114,574,483**

Figure 14

Interestingly, although most public funding bodies will suggest that their strategy is aligned to a certain cross section of the technology readiness level scale, Figure 15 would suggest that this is not always the case. In fact, all the primary funding bodies are supporting research that spans the range of research maturity in terms of TRL.

It is interesting to note that Industrial sources are, on average, funding low TRL research than funding bodies such as Innovate UK and the EU framework and new horizons programs. It is believed this is a reflection of the need by companies to understand the fundamental and basic science behind additive manufacturing before they are in a strong commercial position to adopt the technology.

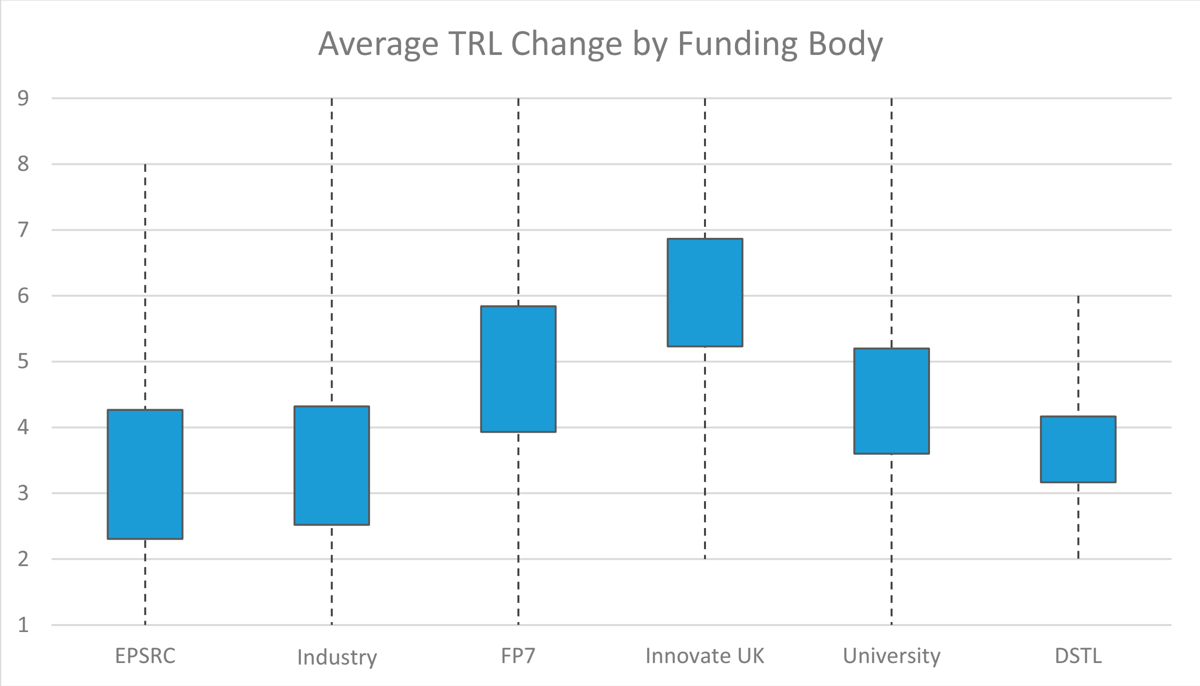

Figure 15

Conclusions

Funding has grown, leading to higher engagement from the supply chain

The scale of additive manufacturing research in the UK has grown substantially since 2012, with a higher number of participating organisations and a greater amount of investment from funding bodies, academia and industry. This broad uptake indicates that many of the barriers to the adoption of additive manufacturing and limitations of the technology identified in the SIG 2012 report are being addressed. The concerns raised in 2012 relating to missing links in the additive manufacturing supply chain appear to be lessening, as there is now higher engagement from a wider range of sectors and supply chain actors such as software and materials development organisations.

Research is focussing on the fundamentals

Although additive manufacturing research funding spans a wide range of sectors, the majority of research investment has been made where there in is an undefined application area or beneficiary sector, such as in the development of enabling technology or materials for additive manufacturing There has been high growth in funding for research with focus on the fundamental science of additive manufacturing with increased activity and spend on low-TRL projects. Organisations such as the EPSRC Centres for Innovative Manufacturing in Additive Manufacturing and Laser-Based Production Processes are pursuing research agendas with an emphasis on fundamental science, while commercial organisations are also engaging in lower-TRL research. There are several possible explanations for this shift in research focus. It may be because early interest in the commercialisation of additive manufacturing left companies unable to reach high-TRL levels without first addressing fundamental science requirements. Alternatively, it could be because industrial organisations have brought additive manufacturing research that is close to commercialisation in-house to protect intellectual property; it was beyond the scope of this report to look at research funded solely by private investment. Another possible explanation is that as a greater number of sectors become involved in adopting additive manufacturing there is an increased demand to make the technology and materials fit their specific sector needs, requiring a return to fundamental science.

Industry is preparing to adopt additive manufacturing more widely

In the SIG 2012 report it was noted that a barrier to adoption was a lack of understanding about additive manufacturing technology. From the recent data analysis it is evident that an increasing amount of research is being carried out into developing additive manufacturing for commercial use and application. A significant amount of research focus has been on product redesign for additive manufacturing and enabling research such as development and characterisation of materials for additive manufacturing and methodologies for quality control and assurance. The analysis has also shown that there is less emphasis being placed on research into process innovation and development. This may indicate that for certain technologies such as metallic powder bed, industry is confident that the fundamental additive manufacturing technology is capable and so now needs to develop the surrounding supply chain to enable adoption. Similarly, there is evidence of industrial demand for skilled engineers, designers and scientists with an education in additive manufacturing the Centre for Doctoral Training in Additive Manufacturing has received high levels of support from industrial organisations. This report has found evidence of funding for a variety of Higher Education activities including PhDs, Masters and Fellowships. Although this report gives no coverage to lower level skills training, it is anticipated that the outcome of the current funding structure for additive manufacturing training will result in overall growth in the UK's additive manufacturing capability.

Commercial exploitation is still low

The SIG 2012 report concluded that there had been very little commercial exploitation of process innovation, with no major UK-based machine vendors active at the time. The SIG 2012 report recommendation to address this gap was that the UK needed to support the development of new technology platforms based on the UK's strengths such as photonics and ink jetting and the stimulation of new business models enabled by additive manufacturing Since the report was published, one major UK-based manufacturer has emerged as a global player; Renishaw plc has driven the development and commercialisation of the metallic additive manufacturing technology that it acquired in 2011 from MTT Technologies Ltd – a beneficiary of TSB funding. There has been substantial activity in developing new technology platforms such as jetting processes in accordance with the SIG 2012 report recommendations but these are still far from commercialisation. Although largely beyond the scope of this data analysis into publicly funded research, the authors also note that there has been little commercialisation of new business models enabled by additive manufacturing in the UK.

The additive manufacturing community is highly fragmented
Despite a high growth in the number of participants involved in additive manufacturing research, organisations are still only networking through projects. Although this network contains centres of critical mass with significant amounts of funding focussed on specific research topics, there is also an extreme long tail effect, with a high number of partners involved in small projects. This indicates that the research base is still as highly fragmented as it was in 2012, as these 'long tail partners' are often not linked into the main additive manufacturing community. The SIG 2012 report called for the formation of a formalised network of additive manufacturing developers and users led by industry to address this issue; however, this recommendation has not yet been taken forward. Similarly, the Foresight 2013 report also recommended that Government take a more targeted approach to manufacturers and develop strategic approaches for disruptive technologies such as additive manufacturing. With such a loosely connected additive manufacturing network, it raises a number of concerns about the strategic direction of the community and the cohesion between the members. Without a formal network, there is little visibility of activity between sectors and supply chain actors; there is also little opportunity for sharing of research objectives and outcomes between community members. This is likely to lead to some duplication of research activities; it was beyond the scope of this report to identify if duplication is already occurring but with an increasing number of partners and projects, there is inevitably some risk of this occurring. As far as these public funded projects are concerned, steps should be taken to maximise co-operation and networking while minimising the risk of duplication.

Recommendations

To strengthen the UK's position in additive manufacturing and continue to build on the progress made since the SIG 2012 report, the following actions are recommended.

1. A National Strategy for developing the UK's additive manufacturing industry is essential to align the increasing number and diverse skillsets of participants within the additive manufacturing ecosystem and provide direction for research objectives. This national strategy should identify areas for investment based on market requirements defined by a wide range of industries, taking into consideration the UK's wider competencies in areas such as software and design. The strategy should also identify where there is excess research capacity or duplication to ensure that the UK's public funded research and innovation activity is valuable and relevant and delivered with minimum waste.
2. A formal network of additive manufacturing users and developers should be established to provide cohesion between the participants in UK additive manufacturing research, facilitate knowledge transfer and act as a focal point for additive manufacturing in the UK. The network should promote dissemination of research outcomes between horizontally-aligned sectors and co-ordinate research activities between vertically-aligned supply chain actors.

The network should aim to include future users from sectors where there is currently low engagement (such as retail and consumer products); this will lead to the development of new business models that use additive manufacturing and drive wider adoption of the technology.

3. Wherever appropriate, end users of innovations in additive manufacturing processes, materials and design systems should be closely involved in fundamental science research at an early stage. This will provide industry with visibility of future technology challenges / opportunities and ensure that end-goals between industry and research are aligned. In turn, this will enable industrial organisations to build strategies for the adoption of the technology into their products and manufacturing operations, driving growth within the industry.

4. Initiatives to provide skills and education for the UK's future additive manufacturing industry should be continued and widened. As industry increases adoption of the technology, there will be increased demand for a skilled workforce, both within the UK and abroad. By continuing to support Higher Education activities such as PhDs and Fellowships, as well as developing education strategies at the Further Education and Secondary School level, the UK can ensure the supply of a highly skilled workforce for the additive manufacturing industry. This Skills and Education strategy should be developed as part of the national UK additive manufacturing strategy, ensuring the involvement of industrial partners to identify skills gaps and future requirements.

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