connected everything.

industrial systems in the digital age

# Design for Future Manufacturing

**Dr Fiona Charnley and Dr Mariale Moreno**

**Cranfield University**

EPSRC

Engineering and Physical Sciences Research Council

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# Executive Summary

The future of design for manufacture needs to incorporate the specific requirements emanating from the digitisation of downstream activities, particularly manufacturing and services. Without a systematic consideration of these requirements, the benefits of digitisation cannot be fully realised in manufacturing. Although current research has investigated the exploitation of digital technologies within design, manufacturing and services separately, there is a need to research the implications that digital manufacturing and digital services have on design. This will ease the adoption of digital technologies in manufacturing and services and enhance the benefits from their adoption. The key research question is how to design the next generation of products that are digitisation-ready and furthermore enable communication from such products to be analysed and used in such a way that added value is enabled for stakeholders throughout the value chain including the customer, designer, manufacturer, remanufacturers and recyclers.

This report investigates the importance and value of design for the future manufacture of industrial systems in the digital age to support the sustainability of the UK economy, environment and society. Interviews with industrial and academic experts in the field of design for manufacture have been analysed, alongside an examination of existing investment and thought-leadership, to identify trends, opportunities and challenges that UK manufacturing is facing regarding the design and manufacture of 21st Century Products, Services and Systems. Digitally enabled design is identified within this report as a pivotal catalyst to realise the vision of a transformational industrial system in the digital age. Specifically, design, when supported by emerging technologies for manufacture can enable: organisations to innovate faster through the use of 3D printing and digital twins, the generation and realisation of new value propositions and business models through the Industrial Internet of Things and data analytics, and the development of personalised, customised and adaptable products to meet intrinsic consumer requirements through the analysis of user behaviour and open innovation practises.

Although the value of design for manufacture is highlighted in several key reports including the new Industrial Strategy, evidence suggests that the value of design is misunderstood by manufacturers. Furthermore, much of the research and development in digitally enabled design is taking place in High Value Manufacturing sectors such as aerospace and automotive whilst other sectors such as consumer goods are yet to realise the benefits. New capabilities are required to equip designers with the skills necessary to effectively communicate and demonstrate the value of design at all levels of a business and across industrial sectors. New technical and scientific skills are also required as 21st Century Products become increasingly complex and integrate layers of physical, digital and networked componentry. The most transformational technologies currently influencing design for manufacture include: Additive Manufacturing, the Internet of Things, Artificial Intelligence and Robotics and Visualisation and Immersive Technologies. However, as 21st Century Products will be designed and manufactured using highly integrated systems that will enable customised processes and product characteristics, through the advancements in energy, material science, nanotechnology, sensors and robotic technologies, it is suggested that the realisation of exponential innovation will require an amalgamation of technological capabilities. Furthermore, as the gap between the designer and consumer decreases thanks to new digital platforms, challenges concerning intellectual property, data security, data sharing, trust and privacy will become even more imperative. The report concludes by presenting some of the short-mid and long term research challenges that will need to be addressed to fully realise the potential of digitally enabled design for the manufacture of future industrial systems in the digital age.

# 1. Introduction

The United Kingdom (UK) manufacturing sector makes a significant contribution to the UK economy accounting for £177bn gross value added (GVA) in 2016.[1] The UK is still one of the top ten manufacturing nations in the world (the eighth largest in 2017) and is the third largest in the EU. It employs 2.6 million people directly, and about 5.1 million across the whole manufacturing value chain. The sector accounts for 70% of business research and development (R&D) and 14% of business investment.[2] Despite growth in the sector, the UK must not be complacent and should capitalise on the implementation of digital technologies to increase productivity and growth as well as to create new markets. Design is a pivotal catalyst to realise the vision of a transformational industrial system in the digital age.[3]

It is well known that design adds value to the UK economy, as the skills, principles and practices of design are now widely used across economic sectors, from banking to retail.[3] Good design can help to commercialise technology, accelerate exports to the world market and exploit the UK's strengths in advanced manufacturing. However, the UK manufacturing industry is reliant on implementing design to facilitate its strength and on-going success. The sector, and especially small and medium sized enterprises (SMEs), have to understand the value that design can bring and adapt to the fast pace of development in technology that is disrupting the way we work and live.[4]

In recent years, we have seen great advances in technology, from 3D printed food products to self-driving vehicles, indicating that every part of the UK economy will be affected by the fourth industrial revolution. However, historically the UK has struggled to translate scientific and technological developments into good value propositions[4], and predominantly the cutting-edge R&D takes place in high performing sectors such as aerospace, transport and the built environment.[2] As such, the High Value Manufacturing (HVM) sector is leading in the implementation of digitalisation in design, manufacturing and servitisation to support and drive the UK's digital industrial revolution. Although current research has investigated the exploitation of digital technologies within design, manufacturing and services separately there is a need to research the implications that digital manufacturing and digital services have on design not only within a HVM context, but also for the manufacturing of everyday goods and services. The future of design for manufacture needs to incorporate the specific requirements emanating from the digitisation of downstream activities, particularly manufacturing and services. Without a systematic consideration of these requirements, the benefits of digitisation cannot be fully realised. Hence, this report aims to explore how to capitalise from design for future manufacture to develop 21st century products that are digitisation-ready, adding value to the UK economy. To achieve this aim, this report focuses on answering three key questions:

1. What are the implications of digital manufacturing and digital services in design?

2. How can industry take advantage of emerging tools, techniques and platforms to design the next generation of products that are digitisation-ready?

3. How can industry take advantage of emerging communication systems to analyse and use data to design the next generation of products through enabling added value for all stakeholders in the value chain?

With these questions in mind, twelve thought-leading design and manufacture experts were consulted through an online and face-to-face questionnaire. They were specifically asked to comment on the trends, opportunities and challenges that UK manufacturing is facing according to three key areas that are transforming the design and manufacturing landscape:

- **Current industry transformation for 21st century products:** In this area, the transformation of design capabilities in a digitalised manufacturing system were explored and ways in which design skills could be adopted to bring added value and competitive advantage was investigated. The transformation of supply chains from long and decentralised to short and distributed was considered alongside the emergence of new business models.

- **Tool, techniques and platforms for 21st century products:** In this area, the most influential technologies and current trends that are transforming the design landscape within the manufacturing sector are identified and discussed, as well as their enablers.

□ **Data-driven and human-centric trends for 21st century products:** This area investigates how a digitally connected economy can be realised by creating value from large scale data that can be used to generate insights and innovation. It also centres on understanding the rising power of consumers to meet long-term needs through personalisation, customisation and co-creation.

In addition, insights from two high profile events on Design and Manufacture[a] informed each of these key areas. These activities were useful to reveal research opportunities for design and manufacture of the next generation of products, and to unveil the role that design for future manufacture plays in the development of future industrial systems and its value to the UK economy. After exploring the transforming landscape, current research funded by the UK Research Councils (RCUK), specifically the Engineering and Physical Sciences Research Council (EPSRC) and Innovate UK were examined. This helped to categorise past and current research, as well as academic and industrial leaders in this thematic area, so that current gaps and challenges could be identified. Finally, future research opportunities for design for the future of manufacturing are proposed.

## 2. Current industry transformation for 21st century products

In 2013 the UK government set a 2050 vision for the manufacturing sector in which it was foreseen that a constant adaptability will pervade all aspects of manufacturing, from R&D and innovation, to production processes, suppliers and customer interdependencies.[5] However, to achieve this vision, it is important that firms are capable of understanding design capabilities to adapt to the rapid pace of technology within the manufacturing sector to better respond to the changing global markets and customer needs. The current transformation of manufacturing systems towards digitalisation, has had an effect on how products are designed, made, offered and ultimately used by consumers. Thus, it is important to understand how digital technologies are transforming the manufacturing industry.

### 2.1 Transformation of design in a digitalised manufacturing system

According to the World Economic Forum[b], a $1000 trillion opportunity could be realised by industry and society through the adoption of digital technologies.[2] In the UK, the application of digital technologies such as artificial intelligence (AI), robotics, data analytics and additive manufacturing (AM) have already made transformational improvements to productivity where HVM businesses have exploited their potential.[2] However, there is still an opportunity to deploy this potential further to enable a flexible production system. Small players who can invest in design of better products are particularly well positioned, with the opportunity to repair and replace parts in shorter lengths of time, modify existing parts for improved performance, enter new markets and develop new business models that will allow them to be more competitive.[6]

The digitalisation of manufacturing systems is transforming the industrial landscape, and this transformation has an effect on design; meaning that new design capabilities have to continue to develop at the fast pace of this transformation. Despite designers being privileged with their unique capability of combining a range of different skills, tools and technologies to deliver new ideas, goods and services[7], designers have to be better equipped to communicate high value-propositions to manufacturers, particularly to traditional manufacturers. This research identified that one of the biggest challenges between designers and manufacturers is the lack of effective communication. This has resulted in the deployment of different technologies that are either not suitable for the product requirements, or do not fulfil user demands. One possible reason for this miss communication was found to be the perception from manufacturers that design is just about materials and manufacturing specification and not about problem solving. The latest report from the Design Council[3] reveals that design delivers 21st century skills contributing £209bn to the UK economy. These skills range from the ability to visualise future possibilities or understand user needs, to technical skills using digital technologies or physical materials. Thus, manufacturers need to understand the value of these design skills in the future of manufacturing

[a] Design for Manufacture Summit. At the Oval Pickle Factory, London, E2 9DU. December 7th, 2017. http://dfmsummit.com/london/december2017 and Manufacture 2075 at Cranfield University, Cranfield MK43 0AL. December 5th, 2017. https://www.cranfield.ac.uk/events/manufacturing-2075-landing/manufacturing-2075-2017

[b] Digital Transformation Initiative Unlocking $100 Trillion for Business and Society from Digital Transformation. January 2017 in collaboration with Accenture.

by having senior managers that are willing to invest in design and measure its success. Responsibility also resides with designers who need to learn how to sell the competitive advantage that design brings, as well as the UK government who should invest in encouraging younger generations to follow careers that support creative and design engineering skills.

The research also uncovered that the integration of digital technologies in new product development and manufacturing systems has been implemented in silos. For example, in some areas of the manufacturing sector the adoption of digital technologies is still in its infancy where as in other areas, such as HVM, it is scaling fast towards a full industrial digitalisation.[2] In addition, every day we use devices that have 'digital' and 'smart' capabilities which are transforming society. However, extending this concept to a digital infrastructure for supply chains still needs to be fully explored.

Whilst manufacturing processes and products become more advanced, 21st century products could be ever more complex than before. As digital componentry meets physical materiality of products, designers need to think about the different physical digital and networked layers of their products e.g. the device and materials to operate, the operations being delivered, the network in which to operate, and the content displayed.[8] However, research findings revealed that digital fabrication could also enable speed iterations and modifications within the design process as products can be digitally and physically prototyped several times before launching in to the market, making the process more flexible and adaptable to rapid changes in consumer demand. Other complexities arise from the development of new materials, such as electroactive polymers and thermal bimetals which will drive new design requirements and the need for additional skills. Thus, it was found that research should focus on how high value engineering products with cutting-edge materials and technologies can be designed that also continually adapt to users' changing needs. In addition, further collaboration between different manufacturers and sectors is needed to allow a design and manufacture integration, as it would be almost impossible to conduct all the R&D and deployment of a new product in house.[9]

Design and manufacture integration can be seen in the following examples for HVM and the consumer goods sector: Through the use of sensor technologies and data captured directly from their engines, Rolls-Royce are able to analyse information across an engine's whole life cycle gaining ever increasing efficiency when the engine is produced, used, and maintained predicting life-span expectations[c]. In contrast, consumer goods manufacturer Adidas, is capitalising on design and manufacture integration with their SpeedFactory Concept[d] where athletes in specific cities across the world can use technologies such as a 3D scanner and augmented reality, as well as data analytics, to co-design their ideal trainer. The data is sent to a fully digitalised and localised manufacturing facility to be produced closer to them. These examples, depict how this integration will allow a closer interaction between user-designer-manufacturer, through agile interconnectivity and the use of data; driving new business models in which technology can transform not only the way products are developed and manufactured, but also the way they are purchased and used. Other identified trends that could emerge with this integration are a) having more connected and transparent supply chains and open opportunities for new comers to develop their own virtual supply chains, b) more effective value creation as good ideas can be turned into market opportunities without the need for expensive capital assets and factory capacity, as products are as much about software as about physical objects and c) enabling a circular economy by using data flows to enhance sustainability of design and manufacturing value chains by reducing their resource use and impact on the environment.

## 2.2 Transformation of supply chains and business models

UK manufacturing relies on complex and highly integrated supply chains. Digital technologies could revolutionise the way that supply chains operate. They could facilitate a transition to a fully connected supply chain network that allows manufacturers to respond more quickly to temporary disruptions and to be more efficient in the production and delivery of goods.[2] In addition, digital technologies are reducing the distance between the manufacturer and the consumer, allowing manufacturers to bypass traditional intermediaries. The digitization of manufacturing, alongside the exponential growth of

[c] http://rolls-royce.com/products-and-services/marine/services/management-services/power-by-the-hour.aspx

[d] http://www.adidas.co.uk/speedfactory

subtractive and additive digital fabrication technologies and robotics, has made manufacturing more repeatable and portable, resulting in the emergence of distributed small scale local manufacturing systems.[9] This trend alongside other prominent trends such as servitisation, personalisation and prosumption[10] is making manufacturing more agile, but also have new implications for design. The so-called democratisation of design enabled by digital manufacturing technologies such as additive manufacturing combined with information communication technologies (ICTs), allow users to be more active in the design and manufacture of their own products becoming prosumers within a global manufacturing community.[11] Take for example MyMiniFactory.com, an online platform through which people can share 3D printable files to be downloaded by other users and 3D printed for free. The digitalisation of design and manufacturing has also enabled new distributed business models such as OpenDesk, which is a global platform that connects designers, local machine shops and users to design and produce durable simple furniture that can be produced locally using digital CNC fabrication tools. Their goal is to reduce the environmental impact of shipping, increase local employment and provide consumers with customizable designer furniture for a fraction of the retail price.[12] This research found out that if manufacturers want to survive in this space, they will need to create more value for consumers, by providing useful information, helping people make better choices and allowing buyers to experience products in new ways. Hence, design and manufacturing practices will need to engage more effectively and more frequently with consumers to narrow the gap between prototype and product and move away from build-to-stock to build-to-order.

The redistribution of manufacturing systems has also enabled emerging business models based on delivering platforms and access to products, instead of ownership. Hence, the creation of value has shifted from delivering physical objects to enabling access. This has created a movement called the 'Sharing Economy' in which businesses can commoditize sharing of underutilized goods enabled by digital infrastructures. This model has resulted in the creation of successful companies such as Uber and Airbnb. However, manufacturers can also capitalise on the opportunity of selling access by investing in the R&D of products and services. Take for example Phillips[e], who have re-designed their lighting business to offer lighting as a service. Changes in the way in which products are offered to consumers has significant impacts for designers. In cases where the ownership resides with the manufacturer, products are required to be durable with longer lifetimes yet at the same time easy to disassemble for upgrade, refurbishment and remanufacture.

In this research, it was found that there is an increasing focus on automation of manufacturing as a means to reduce western manufacturing costs to a level where we can compete with lower cost manufacturing centres, IoT and robotics are both supporting this transition. To maintain a market differentiation there is a constant parallel focus on quality and performance, big data and additive manufacturing are both geared towards this but are not alone, individualized design, short production runs, design-to-print of legacy products to increase longevity of products all gear towards the market value proposition and to some extent may be strong enablers for the circular economy.

This has been seen in the UK with some start-up pioneers that use the power of technology to deliver new business propositions with a circular economy strategy. Forward thinking manufacturers such as RYPE Office bring office furniture back to its original performance using advanced technologies. Their entire business model is based on the customisation and re-manufacture of office furniture. Their case highlights the opportunity for manufacturers to implement the principles of a circular economy to deliver further efficiency and increase added value by supporting advances in flexible automation of design and manufacture.[2] The use of technology to enable circular business propositions have implications on design, as product integrity could be assessed with the use of sensor technologies[13] influencing their design to be properly, maintained, reused, and remade.[14]

## 3. Tools, techniques and platforms for 21st century products

Digital technologies have the potential to add US$14.2 trillion to the world economy over the next 15 years.[2] 21st century products will be designed and manufactured using highly integrated systems that will enable customised processes and product

[e] https://ellenmacarthurfoundation.org/case-studies/selling-light-as-a-service

characteristics, through the advancements in energy, material science, nanotechnology, sensors and robotic technologies. Technology advancements can no longer happen in silos and thus in order to see exponential innovation, the application of a particular technology in the design and manufacturing landscape will need to follow a complete amalgamation of technological capabilities. The biggest advancements in technology that are having a great influence in the design and manufacturing landscape are: Additive Manufacturing, Big Data Analytics, Artificial Intelligence (AI), Robotics, the Internet of Things (IoT), wearable technologies, virtual and augmented reality amongst others. According to the interviewees, the most influential technologies that are transforming the design landscape within the manufacturing sector, are explained below:

## 3.1 Additive manufacturing

Also known as 3D printing, is where objects are created by adding layers of material one on top of another until a 3D object is complete. The technology is used for rapid prototyping, manufacture, repair and replace of end use parts.[6] Additive technology could offer a value of £72.1bn to the UK economy with additional benefits introduced through design innovation and downstream application of new capabilities.[2]

Interviewees stated that additive manufacturing (AM) is the most influential technology that has revolutionised the design landscape. According to the interviewed experts, AM is providing new manufacturing methods, as well as giving designers the possibility to be much more creative by allowing them to shape products with unthinkable structures with materials that in the past were considered to be too difficult to form into complex shapes. In addition, it has influenced design processes as there is no need to design and produce a costly tooling before starting to make a component, as objects can be directly fabricated from a digital design. AM makes it possible to produce one off items or small batch sizes at reasonable costs, and helps to reduce inventory risks as goods are made to order. In addition AM enables highly customisable and personalised designs that can be easily shared in the form of digital files, facilitating modification and customisation of components and products.

According to the interviewees, AM technology is primarily being used in 1) the makers' community to experiment with new designs and materials and 2) by HVM to create parts at low volume. However, it is expected that in coming years the range and scale of AM will extend to lower-value, and high-volume items. According to the Made Smarter Review[2], the UK is well positioned in the R&D of AM technology for high performance applications such as medical and aerospace. Significant investment has been made to increase capabilities through funding streams accessed by universities, catapults and other organisations, expecting these organisations to invest up to £600m in AM over the next 5 years.[2] Despite the potential application of this technology in the UK manufacturing sector, only 17% of UK companies have experience with AM. This lack of experience is attributed mainly to SMEs.[2] Part of the problem, is that UK manufacturers see the technology just for its prototyping applications, but not for its full production capabilities. Apart from the lack of knowledge of the full application of AM, there is a lack of skills and investment capital to introduce this technology. Hence, the report makes a call for action to fund a co-ordinated approach that pulls together UK's consolidated research in efficiency and material choice, design, production and testing to demonstrate and capitalise from the capabilities of AM in new manufacturing sectors. In addition, the findings revealed that leadership on Design for AM is needed to address some of the current concerns of digital fabrication including: the specification of raw material and product testing standards for AM and managing the intellectual property (IP) of open digital files to be customisable and upgradable.

## 3.2 Internet of things (IoT)

The Internet of Things (IoT) combines cutting-edge machines, advanced analytics and plethora of devices that connect with each other through communication technologies. That connectivity allows the data collected by those devices to be monitored, exchanged and analysed to deliver valuable insights for industrial companies.

IoT facilitates the generation of large amounts of data that could be analysed and used to improve design and manufacturing processes. It is expected that IoT will boost the UK economy by £352 billion by 2030,[2] and will allow design and manufacturers to follow a data driven approach to innovation, unlocking new business opportunities worth £66bn to the UK Economy.[15] This opportunity can only be realised through upscaling industrial and government investment in the Industrial Internet of Things (IIoT). IIoT brings together a number of connected technologies to drive more informed and faster business decisions through the analysis of data collected by those devices. To capitalise from IIoT, investment in a connectivity infrastructure, including Low Powered Wide Area Networks (LPWAN) and the next generation of 5G internet, is needed to underpin the factories of the future.[16] The UK, has already invested in R&D IoT technology through the IoTUK programme, a network of academics (e.g. the EPSRC PETRAS Hub), hardware accelerators (e.g. Start-up Bootcamp), large-scale demonstrators (e.g. NHS testbeds) and dissemination models (e.g. Future Cities Catapult); to support IoT development and uptake in the UK. However, it is essential to continue investing in the application of the research and development of these technologies, as industry sees that the application of IoT to be fundamental to their business success, in areas such as customer and marketing analytics, product use, and predictive and prescriptive maintenance of machines.[17] Thus, it is recommended to steer early research into industry through testbeds in which leading innovators and researches could test their technologies and ideas in real world industries.

The research revealed that the interconnectedness that IoT represents, can allow the design process to happen in real time, as data can be used across different design and manufacturing technologies enabling constant iteration in the process to maximise its performance. Several interviewees referred to ‘Digital Twins’ as an enabler of IoT to improve the design and manufacturing process in real time. ‘Digital Twins’ refers to a digital replica of physical goods, processes and systems to create living digital simulations able to monitor and change their physical counterpart, through the use of artificial intelligence (AI), machine learning, and data analytics. Through this research, it was found that this technology is in its infancy and there are still many challenges to twin the physical component with the digital one to make decisions through real-time data, and hence this should be further explored. In addition, distributed ledger technologies such as Blockchain, can also be used to promote broader opportunities for more localised and personalised design and manufacture structures. However, it was found that Blockchain still faces key challenges on transparency and security. This challenge spreads out to all IoT applications, as manufacturers are little aware of cybersecurity strategies having little investment in the prevention of cyber-attacks.[2]

## 3.3 Artificial Intelligence and robotics

It has been estimated that Artificial Intelligence (AI) in industry will offer a value of £232 billion to the UK economy by 2030.[1] AI, whether in the form of augmented intelligence, cognitive computing or machine learning; is set to radically transform the way we design and manufacture things. This would not be possible without the vast amount of data to deliver value from AI through the use of cost-effective data capture devices and sensors. For design and manufacturing AI will have greater value for predictive analytics, by analysing and optimising processes through data collected across the supply chain. As our research highlights, we are increasingly embedding intelligence into products to create data loops that are helping us improve design and material capabilities. Ultimately re-design, re-manufacturing and re-use will become more adaptive and resourceful because machines are learning about design and material properties. As such, research conducted by the University of Huddersfield highlights a need for industry to invest more in AI mechanisms to address predictive maintenance and real-time condition monitoring and the introduction of integrated production planning and vertical scheduling systems throughout their supply chain.[1]

AI-based machine learning is possible by the application of ElecTech. ElecTech refers to the industrial application of electronics, electro-technical and embedded software technologies. It is a core part of the digitalisation of manufacturing and robotics providing many essential skills, components, and capabilities. The application of automation and robotics within UK industry provides a value of £183.6 billion to the UK Economy.[2] This research found that robotics and automation will enable flexible manufacturing operations to perform new design and manufacturing tasks that could address challenging requirements. In addition, new design challenges will emerge, as with the rise of robots and AI, design specifications would need to be thought for the right user, which in many cases this would be a combination of humans and AI.

The UK has demonstrated world leading research in robotics for different sectors, but focuses mainly in autonomous vehicles. Recognised hubs are Edinburgh Centre for Robotics, Sheffield Robotics, Bristol Robotics Lam and Imperial College’s Hemlyn Centre. Furthermore, the UK has highly innovative robot companies including Shadow Robot company, Peak analysis and Automation, Ocado Engineer and Dyson – who have invested tens of millions into robotics for household appliances.[2]

### 3.4 Visualisation and immersive technologies

Advanced visualisation enables the effective communication of data, concepts and ideas to enable greater productivity, reduce risk and improve quality. This can include CAD design through the adoption of immersive technologies (virtual, augmented and mixed reality) for digital twins and virtual prototyping.[2] Virtual Reality (VR) immerses users in a computer-generated world, whilst Augmented Reality (AR) overlays digital information onto the physical world. Both technologies are reshaping existing ways of doing businesses, and are expected to reach a value of £801millon by 2021.[2] These technologies are already being used by manufacturers to support the development of complex assemblies, planning for the maintenance of equipment and products, the provision of remote expert support, as well as higher quality assurance and increased productivity. VR/AR has been also used to validate certain designs, as well as to virtually prototype products and manufacturing processes of those products. It was found that these applications helped to de-risk in the design stages and to predict failure before it enters the manufacturing floor. It was also found that the challenge to make immersive technologies effective, is the development of standards to allow data extraction, protection of IP and the integration of software and hardware platforms. In addition, it was found that connectivity between physical and virtual devices, alongside the effective collection of data has to improve to create beneficial and accurate virtual environments.

## 4. Data-driven and human-centric trends for 21st century products

Each day, around five million devices link up with each other, with the internet or with both. There are around 6.4 billion data-communicating objects in the world today.[2] AI and data analytics are already creating enormous opportunities to understand more about us, from our health to what we like to buy. This, along with rising consumer power to target unmet needs around personalisation, customisation and co-creation; has allowed an emerging design process in which consumers become co-creators of unique products tailored to their own needs, such as a trainer made for your own foot or a drug customised to treat specific cancer cells. The research found that despite the continuing importance in the role of design, there is a growing demand from consumers to engage in the creation, or at least conceptualisation, of the products they buy. Take for example Lego Open Innovation Platform[f], which allows 'Lego Geeks' to propose new designs that are rated by other Lego users, and if they have enough support, they are produced by Lego. This interaction with consumers, has resulted in designing products and services that deliver superior experiences, hence value resides not just in manufactured products, but also in the information and experiences those designs facilitate.[18] In this case the role of design is as a facilitator of the development of these experiences through an ecosystem of add-ons between the physical and digital products, where they can be tested through business model prototyping.[8] These ecosystems are facilitated by digital/physical platforms with set standards and governance that facilitate third-party participation and interaction. An example of this is Arduino[g], an open-source electronics platform based on easy-to-use hardware and software. Through the open-source platform, Arduino collects accessible knowledge that improves their value proposition.

None of these new emerging business models would exist without the use of digital technologies which are making the design and production process more flexible and reconfigurable, allowing new product and service offerings at a more efficient cost. In addition, data-driven innovation is making it possible to use big data analytics to test concepts with experience prototypes in a quicker and accessible manner. Take for example Philips Hue[h], which used data to understand touchpoints between the user and the lighting experience to develop their connected lighting system. This research highlights the use of sensors to actively monitor use cases to drive meaningful innovations, which is something that is not fully explored in industry and academia. There are also unprecedented issues regarding sharing data for innovation. Although 22% of consumers are happy to share some data to enable product innovation[18], those consumers expect some sort of incentive - from more personalised products to discounts on next purchases or free upgrades. Thus, trust and privacy mechanisms in the collection and use of data needs to be further explored.

[f] http://ideas.lego.com/dashboard

[g] https://www.arduino.cc

[h] https://www.philips.co.uk/c-m-li/hue

## 5. Value to the UK economy in the future development of design for industrial systems

The UK Government recently launched a new industrial strategy, which recognises the need for investment in research and development on digital technologies for design and manufacturing of the future.[1] Further investments are also required in developing design skills to improve productivity and innovation.[3] Current research highlights the positive impacts of design skills to be central to innovation, contributing £209 billion to the UK economy. Moreover, the impact of industrial digital technology on the UK economy is expected to be over £455 billion for UK manufacturing. The impact of these contributions is suggested to improve industrial productivity by more than 25% alongside social (i.e. increase of jobs) and environmental (i.e. reduce of CO2 emissions) benefits.[2] The analysis of the identified key areas that are transforming the design and manufacture landscape revealed that the value of design for future manufacture has to be further emphasised in future research. Despite this, the UK is already starting to invest in such research projects in collaboration with leading academics, research excellence centres such as the catapults and industry, through the RCUK and Innovate UK. To get a better understanding of the focus of this research portfolio the following section reviews current research related to Design for Future Manufacture, specifically funded by the EPSRC and Innovate UK.

## 6. Current Research Portfolio

RCUK Funding has a cross cutting theme on 'Digital Economy', managed by EPSRC. The 'Digital Economy' theme[i] is supporting research to rapidly realise the transformational impact of digital technologies on aspects of community life, cultural experiences, future society, and the economy. The four priority areas are: a) Trust, identity, privacy and security, b) Digital business models, c) IoT for a service economy and, d) Content creation and consumption. The total theme funding is £146.64 million.

Further research funding from the RCUK that is of interest to this research is the 'Manufacturing the Future' theme[j] managed by the EPSRC. The Manufacturing the Future theme was initiated in April 2011 with 4 priorities: a) 21st century products, b) Digital manufacturing, c) Sustainable industries and, d) New industrial systems. The theme was stablished to conduct research into critical challenges facing the UK today and in the future. The total theme funding is £459.95 million.

In addition, Innovate UK[k] acts as another funding body which enables collaboration between industry and academia to drive productivity and growth by supporting businesses to invest in new technologies, in developing new ideas and making them a commercial success. The priority areas for Innovate UK have a sector focus: a) Emerging and enabling technologies, b) Health and life sciences, c) Infrastructural systems and d) Manufacturing and materials. Emerging technologies and manufacturing and materials were considered to be of particular interest for this report. From the aforementioned sector focus, £137 million is assigned to manufacturing and materials and £86 million to emerging and enabling technologies.

Furthermore, in 2015 Innovate UK launched the Design in Innovation Strategy[19] through which businesses were encouraged to use design to help to boost the application of their investment in R&D projects. The strategy has influenced calls such as Emerging and Enabling Technologies, in which the use of human-centered design was encouraged. As a result of this strategy, in 2016 a call for Design Foundations[l] was released to realise the value of design within companies through projects that could identify high-value innovation opportunities for new products, services or business models.

### 6.1 Relevant research projects

Within the RCUK Digital Economy theme the majority of projects fall into research on Artificial Intelligence Technologies, Complexity Sciences and Engineering Design as per EPSRC classification. From the Manufacturing the Future theme, most projects are in the areas of Control Engineering, Engineering Design, Human Computer Interaction, Human Communication in ICT, ICT Networks and Distributed Systems as per EPSRC classification. Table 1 shows the relevant research projects for this report, funded by the EPSRC under these themes. It

[i] https://www.epsrc.ac.uk/research/ourpotfolio/themes/digitaleconomy
[j] https://www.epsrc.ac.uk/research/ourpotfolio/themes/manufacturingthefuture/strategy/priorities
[k] https://www.gov.uk/government/organisations/innovate-uk/about
[l] https://www.gov.uk/government/publications/funding-competition-design-foundations-2017-round-1/competition-brief-design-foundations-2017-round-1

should be noted that there are overlaps amongst some of the projects across these thematic areas. Despite the high investment on relevant research for this thematic area, it was found that the main focus of these projects is in building capabilities of specific technologies to aid the design process, as opposed to embracing design as a strategic instrument to enable leadership and innovation within the manufacturing sector. Despite this, the Network programmes such as the Network Plus: Connected Everything: Industrial Systems in Digital Age and the Re-Distributed Manufacturing Networks, because of their nature, focused on enabling leadership by integrating different actors to holistically demonstrate design and technology capabilities within the manufacturing sector. The next section reviews the leadership within this thematic area.

# 7. Leadership in the thematic area

The Made Smarter Review[2] acknowledges that at the moment the UK has a fragmented capability in leadership regarding R&D activities. Despite leading in the application of digitalisation for design and manufacture, there is not a clear vision of what the UK is doing well, and what the significant opportunities for further development are. Through this research, it was identified that the key actors that are responsible for driving the transition to design the next generation of products that are digitisation-ready are industry, start-ups, catapults and academics/educators. However, as stated in the Made Smarter Review, to be successful the transition needs more effective co-ordination between these entities. The identified strengths of these actors, as well as the challenges they face to drive this transition, are discussed below:

## 7.1 Industry

It was found that the sectors that are pioneering in their approach to design as a result of the latest technological advances are the aerospace, automotive, and pharmaceutical industries. For example, in the aerospace industry companies like Airbus and Boeing are using digital technology to understand product and manufacturing trade-offs providing more informed decisions at the design stage. In addition, digital technology can allow the development of services within aircraft components, by assessing their performance with the use of IoT. For example, a new Airbus model has around 20,000 individual sensors in its wings, while GE's new jet engines collect 5,000 data points every second. The pharmaceutical industry has seen major advantages in applying advanced digital design techniques, driving a more targeted and outcome-driven healthcare approach. This approach has helped to eliminate non-viable drug candidate formulations earlier in the development process, as well as better predicting the properties and performance of targeted formulations. This approach will be supported by agile manufacturing allowing small-scale production closer to the point of use. Other sectors are also capitalising from the use of technology. For example Premier Foods and Unilever use IoT to encourage food safety and traceability throughout their supply chain, and improving production efficiency, as well as their relationship with retailers, consumers and food services. This integrated monitoring system has also unveiled new consumer trends through the analysis of consumer data.

UK Industry has clear strengths and are leading in areas such as:

- Strong capabilities to develop and adopt technology that supports design for the future of manufacturing,
- Leading the use of digital technology to enable servitisation such as: additive manufacturing, collaborative robots, artificial intelligence, data analytics, and virtual and augmented reality,
- High market capabilities in artificial intelligence and machine learning with over 200 SME's in the field,
- Use of visualisation and immersive technologies to run simulations that aid the design of high value components,
- Having world-class design capabilities by investing in in-house talent,
- The UK has cutting edge design programmes that link business with design. Three of the top ten design schools in the world are located in the UK (i.e. Royal College of Art, the University of Arts, and the Glasgow School of Art).

## Table 1: Relevant funded research projects to inform future research on design for future manufacture

| |
|---|
| **EP/M02315X/1** From Human Data to Personal Experience. University of Nottingham. Derek McAuley. £4,062,954.00 |
| **EP/K014161/1** Cloud manufacturing - towards resilient and scalable high value manufacturing. University of Nottingham. Svetan Ratchev. £2,364,079.00 |
| **EP/K014196/2** The Language of Collaborative Manufacturing. University of Bristol. Ben Hicks. £1,877,604.00 |
| **EP/K014234/2** - Prototyping Open Innovation Models for ICT-Enabled Manufacturing in Food and Packaging. Royal College of Art. Sharon Baurley. £1,673,747.00 |
| **EP/P001246/1** - Network Plus: Industrial Systems in the Digital Age. University of Nottingham. Sarah Sharples. £1,003,586.00 |
| **EP/017567/1** – RECODE Network. Cranfield University. Fiona Charnley. £467,457 |
| **EP/M017591/1** - Re-distributed manufacturing network: The role of makerspaces. Royal College of Art. James Tooze. £467,177 |
| **EP/M017656/1** - 3DP-RDM: Defining the research agenda for 3D printing enabled re-distributed manufacturing. University of Cambridge. Tim Minshall. £467,623 |
| **EP/N005848/2** - Design Your Own Future: Supporting Networked Design Expertise. Northumbria University. David Kirk. £142,188.00 |
| **EP/N010558/1** - Intelligent Mobile Crowd Design Platform. University of Cambridge. Per Ola Kristensson. £289,525.00 |
| **EP/P027482/1** - Embedded Integrated Intelligent Systems for Manufacturing. Loughborough University. Andrew West. £1,608,257.00 |
| **EP/R021031/1** - New Industrial Systems: Chatty Factories. Cardiff University. Pete Burnap. £1,467,376.00 |
| **EP/K014056/1** Theme 7: Visualisation and Virtual Experience. University of Warwick. Professor. Alan Chalmers. £840,939.00 |
| **EP/N005945/1** Ubiquitous Computing Enabled Design. Imperial College London. Leila Sheldrick £295,395.00 |
| **EP/R020957/1** New Industrial Systems: Manufacturing Immortality. University of Bristol. Paul Race. £2,191,901 |
| **EP/K001396/1** Tales of Things: Exhibition and symposium on the Internet of Social Things. Edinburgh College of Art. Professor Speed. £10,000 |

Despite these clear strengths, UK Industry phases some challenges that need to be overcome:

- Develop a more co-ordinated approach to access training on the application of design and technology skills amongst key areas of the business,
- As data is centric to produce 21st century products, it is necessary to invest in cybersecurity measures and training programmes on advanced security processes,
- As data is currency in the digital age, it is difficult for companies to ensure that all information is secured and up to date. Privacy becomes a greater challenge too. As value chains become more digitally integrated, information that was previously only available within an organisation might become more readily available to others,
- Data accuracy is another concern. Greater connectivity could make it more difficult for a company to ensure its data is not modified by unauthorised parties,
- Understanding of what data is meaningful to address specific needs to design and manufacture 21st century products is also a challenge,
- Understanding of what data is meaningful to address specific IP exists as data. Therefore, it can be lost easily. Especially with AD files IP can be a big challenge due to reverse engineering, cloning and production of counterfeit products.

## 7.2 Start-ups

The UK has a strong reputation as an incubator for start-ups, and it is ranked third amongst OECD countries to support such entrepreneurs. Mainly, this is supported by a tax environment that rewards entrepreneurship.[1] There are clear strengths and challenges for start-ups to drive the transition of the next generation of products, as explained below.

Strengths:
- Support of universities to incubate ideas with a mentorship model,
- Start-ups are leading the discussion on how to develop innovative systems of value exchange through the offering of highly digitalised products and services that support a circular economy,
- The emergence of start-ups with creativity and design backgrounds.

Challenges:
- Lack of coordination to bring together large corporations and start-ups to get access to expertise that could help to deploy new technologies into the market,
- Lack of design and digital engineering capabilities in higher management and strategic teams,
- Lack of investment in design to specifically support the early stages of the innovation process,
- Poor levels of adoption of technology due to risks around cyber security, and lack of common standards allowing different technologies to connect,
- Lack of support for digital technology start-ups, causing the UK to fall behind in creating new innovative companies and industries.

## 7.3 Catapults

Catapults were stablished by the UK Government with support of Innovate UK to bridge the gap between business and academia, helping to turn great ideas into reality, by providing access to world-class research and development facilities and expertise that would otherwise be out of reach for many businesses in the UK. To date, there are 10 Catapults with the aim to create a further 20 by 2030. The High Value Manufacturing Catapult and the Digital Catapult are of particular interest to this report and thematic area.

The High Value Manufacturing Catapult[m] looks at the application of cutting-edge technical knowledge and expertise for the creation of products, production processes and associate services which have strong potential to bring sustainable growth and high economic value to the UK. They have seven centres of excellence including: AFRC, CPI, Nuclear AMRC, AMRC, WMG, MTC and NCC.

The Digital Catapult[n] works with companies of all sizes to transform their businesses through digital innovation. They have a priority on SMEs to help accelerate sustainable growth and development in digital innovations to make the UK economy stronger. For larger corporates, the Digital Catapult strengthens the culture of innovation and drives collaboration with the UK's brightest digital innovators, digital experts and applied research.

Within this research it was generally perceived that the Catapults are a strength to the UK, offering a platform to bring together R&D, start-ups and companies. However, it was also suggested that a more integrated approach enabled by a stronger network of collaborators could support more effective development of capabilities in design for future manufacture.

## 7.4 Universities

Within this research, the Centres for Excellence conducting relevant research for this thematic area were identified. Table 2, shows a summary of these centres and their focus. In terms of strengths it was clear that UK universities are driving the research in advanced technologies for the future of design of 21st century products, and there is close collaboration with industry to develop these technologies. However, some of the foreseen challenges were:
- Encouragement of SMEs to offer internships/student placements to raise awareness of design skills that could enhance their company as well as offering new career prospects to graduates,
- Brexit will have an impact on funding and recruitment of talent to bring ideas to life,
- Funding bodies such as RCUK giving large grants in lumps as opposed to having a pathway for small to large grants responding to grand challenges,
- Lack of co-ordination between academics, catapults and research centres to capitalise better on R&D efforts,
- Barriers to accessing industrial infrastructure to conduct research.

m https://hvm.catapult.org.uk/

n https://www.digitalcatapultcentre.org.uk

## Table 2: Summary of Centres for Excellence and their focus

| | |
|---|---|
| **University of Nottingham** | |
| Institute for advanced manufacturing[o] | The Institute for Advanced Manufacturing encompasses an international, multidisciplinary team of established academics in additive manufacturing and 3D printing, advanced manufacturing, advances materials, bioengineering, composites, drug delivery and tissue engineering, food sciences, human factors, machine and condition monitoring, manufacturing metrology, precision manufacturing, process and environmental technologies, and operation management and information systems. Its research portfolio presents a unique integrated, holistic approach to manufacturing and draws upon the expertise of the aforementioned areas. |
| Horizon Digital Economy Research Institute[p] | Horizon brings together researchers from a broad range of disciplines to investigate how digital technology may enhance the way we live, work, play and travel in the future. |
| **University of Bristol** | |
| Engineering Systems and Design research group[q] | Engineering Systems and Design research group is known internationally for it's far reaching stakeholder-needs defined research that is rooted in the application of Systems Thinking. The group also has world-leading expertise in the design and manufacture of high value products and industrial systems. |
| **Imperial College London** | |
| Manufacturing Futures Lab[r] | The Manufacturing Futures Lab provides a focus for the fundamental science and engineering research that will form the basis of tomorrow's manufacturing industries. It also provides a forum for leading academic researchers collectively to develop a strategy for the university in this area and to collaborate with industrialists with interests in science-based manufacturing industries. The Lab is comprised of the following thematic networks: additive manufacturing, agri-food, future electronics, industrial biotechnology, innovation and new business models, innovative production processes, new materials and Nano devices, product design, resource efficiency, robotics, sustainable manufacturing, therapeutics, underpinning chemistry and ICT. |

[o] http://www.nottingham.ac.uk/ifam/research/themes/index.aspx
[p] http://horizon.ac.uk/
[q] http://www.bristol.ac.uk/engineering/research/eng-sys-design/?ga=2.247965060.2084990346.1508948526-342506041.1508948526
[r] http://www.imperial.ac.uk/manufacturing-futures-lab

## Table 2 continued

| | |
|---|---|
| **Loughborough University** | |
| Additive Manufacturing Research Group[s] | The group is a cross-school initiative between Loughborough Design School and the Wolfson School of Mechanical and Manufacturing Engineering. The group focuses on exploring the combination and integration of Additive Manufacturing with other emerging fields of science and technology to realize radically new products, capability, and applications. Within the Additive Manufacturing Research Group, there is the Design for Digital Fabrication Research Group which focuses on new ways of designing that maximize the potential of the latest automated, computer-controlled manufacturing processes. This includes research into new design methods, techniques and tools as well as the psychosocial and economic impacts of these processes. |
| **Cardiff University** | |
| Centre for Advance Manufacturing Systems (CAMSAC)[t] | CAMSAC is an interdisciplinary research centre that bridges the engineering and business disciplines. CAMSAC takes a holistic, interdisciplinary approach, working closely with a whole range of industry partners, from start-ups and small businesses to global multi-nationals. |
| **University of Cambridge** | |
| Institute for Manufacturing (IfM)[u] | IfM research aims to help companies to develop life-changing products and services, build better businesses, create meaningful jobs, and improve the environment for the future; and to help government foster innovation and enterprise to deliver social and economic benefits. Their research focuses on a wide range of manufacturing-related topics including: new materials and advanced production technologies, digital manufacturing technologies and data analytics and how they can be used to transform factories, supply chains and business models, how new technologies can be nurtured through the development phase and turned into successful businesses, and in effective business tools and processes (such as road mapping) that can help organisations achieve their strategic goals. |

[s] http://www.lboro.ac.uk/departments/design-school/research/d4df/
[t] http://www.cardiff.ac.uk/camsac
[u] https://www.ifm.eng.cam.ac.uk

## 8. Research opportunities for design for future manufacturing

This report has investigated and emphasised the importance and value of design for the future manufacture of industrial systems in the digital age to support the sustainability of the UK economy, environment and society. The research conducted has identified current trends, opportunities and challenges that UK manufacturing is facing regarding the design and manufacture of 21st Century Products, Services and Systems. To fully realise the potential of digitally enabled design for the manufacture of future industrial systems in the digital age, a number of research challenges need to be addressed.

**Short – Mid Term Research Challenges:**

With evidence of new and emerging technologies already influencing the way that 21st Century products, services and systems are designed there are significant opportunities to exploit, upscale and share this activity across manufacturing sectors and between technological developments. Some of the research challenges that need to be addressed in the short term include:

- Evaluation of best practise in digitally enabled deign for manufacture to enable knowledge transfer between high value manufacturing and more traditional manufacturing sectors,
- Identification of the capability and technological, scientific and creative skills necessary to design 21st Century products,
- Processes for effectively identifying and nurturing talent to ensure the sustainability of UK leadership in the face of political change,
- Communication and demonstration of the value of design thinking and practise across organisational levels and industrial sectors,
- Development of standardised tools, methods and processes for exploiting existing technology in design and enabling it to become more mainstream e.g. the use of 3D printing to enable rapid innovation and shorter route to market, new value propositions and business models enabled by IoT and data analytics and the development of personalised, customised and adaptable products to meet intrinsic consumer requirements through the analysis of user behaviour and open innovation practises,
- Wider adoption of digitally enabled design for manufacture in SME's and start-ups,
- Exploitation of existing and emerging technology and design thinking to address UK and global environmental challenges.

Section 3 of this report highlighted some of the most transformational technologies currently influencing design for manufacture. As these fields are still emerging each has its own technical challenges that will need to be addressed in the short term to enable effective exploitation by design for manufacture. There is particularly a need to understand the material-process-product-performance relationship. Gathering and managing data throughout design, manufacturing and testing is critical here to informing design and manufacturing improvements. As such, gathering more data in a more automated and consistent manner will be essential and will require a degree of standardization.

**Longer Term Research Challenges:**

As the landscape of digitally enabled design and manufacture continues to change rapidly, alongside the exponential growth of technological development, a long-term roadmap of research needs to be established to position the UK at the forefront of innovation. Some of the longer term research challenges highlighted within this report include:

- New standards to support more effective acquisition, use, sharing, transparency, security and privacy between actors across the industrial system including consumers, designers, manufacturers and government organisations,
- The design of high value engineering products with cutting-edge materials and technologies that also continually adapt to users' changing needs,
- Enable a better engagement with the consumer by using IoT to gather and use consumer data to design and enhance the value proposition, including adding new services to consumer products
- Amalgamation and integration of technological development to facilitate the whole system design of 21st century products, services and processes,

Sections 6 and 7 of this report highlighted what type of research has already been conducted, and thus should inform the development of the proposed roadmap.

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**Faculty of Engineering**
**University of Nottingham**
**University Park**
**Nottingham**
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