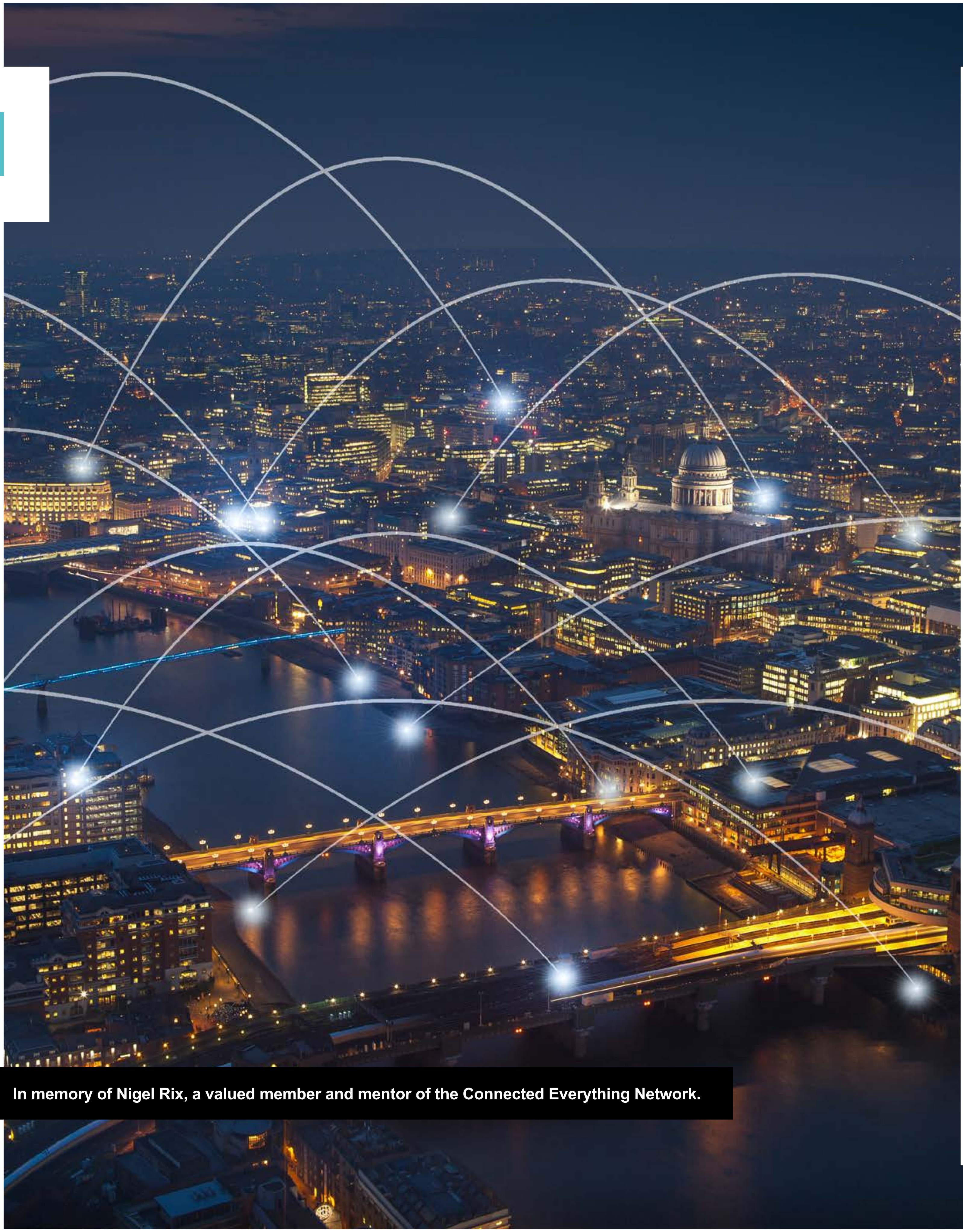
# DIGITAL WORLD 2050



In memory of Nigel Rix, a valued member and mentor of the Connected Everything Network.



# FOREWORD

Manufacturing in 2050 will look profoundly different to today. The products and services we consume, how they get made, delivered and reused across all sectors will need to be delivered by a production system or value chain that delivers at net zero or better.

Digital technology and its successful development and implementation will help enable that and also allow us to reimagine the future of work within engineering and manufacturing. This reimagined value chain has to function effectively in disrupted times offering resilience in product delivery and to the local economies, engaging local communities and inspiring the next generation to innovate further.

Over the past six years, the Connected Everything Network has engaged with many different experts from a range of backgrounds. These experts have brought different academic, technical and industrial perspectives to some of the challenges that we face as we aim to increase the extent to which we embed digital technologies in the manufacturing life cycle, and the impact of those technologies on efficiency and productivity.

The 2050 report has brought together these views and framed them across a series of themes which take a holistic approach. One of the original goals of the Connected Everything approach was to bring new voices and insights into the debates and challenges facing the development and implementation of digital manufacturing technologies; this report presents the outputs of discussions between those new voices and perspectives and those with extended valuable experience in the reality of implementing digital manufacturing technologies in a range of sectors and settings.

This report compellingly outlines the challenges, the UK strengths and the opportunities for the UK in leading during this transformation and how we can bring together the manufacturing, academic and technology strengths to deliver UK prosperity that has a global impact. The coming together of many across those areas to feed into this reports and the alignment of ideas is the template for how we can accelerate towards that net zero manufacturing future.

**Sarah Sharples,** Chief Scientific Adviser for the Department for Transport and Professor of Human Factors in the Faculty of Engineering at the University of Nottingham

**Chris Courtney,** CEO of the National Manufacturing Institute Scotland and UK Research and Innovation (UKRI) Challenge Director for Made Smarter Innovation

# EXECUTIVE SUMMARY

Digital technology is becoming embedded throughout manufacturing and society, so it has a critical and growing part to play in addressing manufacturing challenges and delivering a sustainable and resilient future. Maximising digital technology's contribution will depend on the decisions we make today, and the actions of governments, industry and funders.

Connected Everything is an Engineering and Physical Science Research Council (EPSRC) funded Network Plus that aims to accelerate multi-disciplinary collaboration, foster new collaborations between industry and academia and tackle emerging challenges which will underpin the UK academic community's research in support of people, technologies, products and systems for digital manufacturing. Connected Everything has embarked on horizon scanning activities, undertaken in collaboration with industrial partners and policy makers, to generate new knowledge on the challenges and opportunities for Digital Manufacturing practice and policy in 10, 20 and 30 years' time.

The horizon scanning activity has been focused on four cross-cutting themes that emerged from consolidation with the digital manufacturing community, via surveys and workshops and guidance provided by the Connected Everything Executive group.

Throughout 2021 and early 2022, Connected Everything hosted roundtable discussions on each theme to share perspectives and research for understanding the future of digital manufacturing. Participants were also encouraged to recommend literature and case studies, which have been analysed to support the conclusions drawn from this report. The roundtable topics were:

1. **Industrial Digital Technologies in 2050:** Industrial digital technologies (e.g. robotics, machine learning, virtual reality) underpin and enable digital manufacturing. Emerging industrial digital technologies are having far-reaching implications for how we produce things, exchange information and interact across supply chains and with customers. This theme identified both future uses of industrial digital technologies (e.g. large-scale system modelling, sensors to measure key variables and reprogrammable production lines) and emerging technologies (e.g. nano embedded sensors, edge Artificial Intelligence (AI) and continuous machine learning) that offer exciting opportunities for manufacturers to meet today's and tomorrow's challenges.
2. **Digitisation and The Manufacturing Workforce of the Future:** As the adoption of digitisation accelerates, the impact on the manufacturing workforce is currently uncertain. This theme aims to understand the way that this will change the fundamental nature of work, and the way that we, therefore, design the technology and systems which will enable the future workplace is key to the delivery of future safe, effective and productive workplaces. New opportunities for the manufacturing workforce emerged, including improving manufacturing transparency, aiding decision making, reducing knowledge barriers and formation of new manufacturing roles.
3. **Digital Support for Achieving Net Zero Manufacturing by 2050:** The manufacturing and construction sector is the third largest sector in terms of carbon emissions. While there are many routes to net zero, digital technologies are becoming central to all modern economies and understanding how they can help manufacturers achieve net zero by 2050 is crucial. Five clear methods by which digital manufacturing can support the journey towards net zero manufacturing were proposed, which included the digital-enabled circular economy, design of the next generation of sustainable products, data-driven sustainable decision making, real-time data of supply chain emissions and enabling new clean energy sources.
4. **Digitally Enabled Manufacturing Resilience:** Over the past two years, manufacturers have faced unprecedented disruption with the combination of the UK leaving the European Union, the global pandemic and the humanitarian disaster in Ukraine, combined with soaring transport, energy and raw material costs. This theme explored both how digitisation can play a key role in making manufacturing systems more resilient (e.g. enable agile manufacturing, enable collaborative resilience and enable new resource streams) and also identified what risks and challenges digitisation poses to resilience (e.g. understanding process manufacturing vs discrete manufacturing resilience requirements, lack of trust in digital manufacturing, compliance with regulation, incorrect application of digital solutions).



A particular aim of the roundtables was to identify recommendations to improve policy evidence gathering, policy analysis and policy-making to support addressing the challenges from each theme. A total of 27 recommendations emerged from the Connected Everything roundtable discussions which included: encouraging researchers to quantify digital solution impact; supporting the design of sustainable products; providing financial incentives for manufacturers to decarbonise; and removing legislation preventing waste from being used as a viable alternative resource. Across the four themes, five recommendations emerged strongly and consistently and are illustrated in **Figure 1**.

**Connect digital technology developers to manufacturers**
Greater support is needed to connect manufacturing businesses with the UK innovation community, creating opportunities, increasing productivity and solving industry challenges. This will ensure future digital manufacturing research will develop solutions that fit manufacturing priorities.

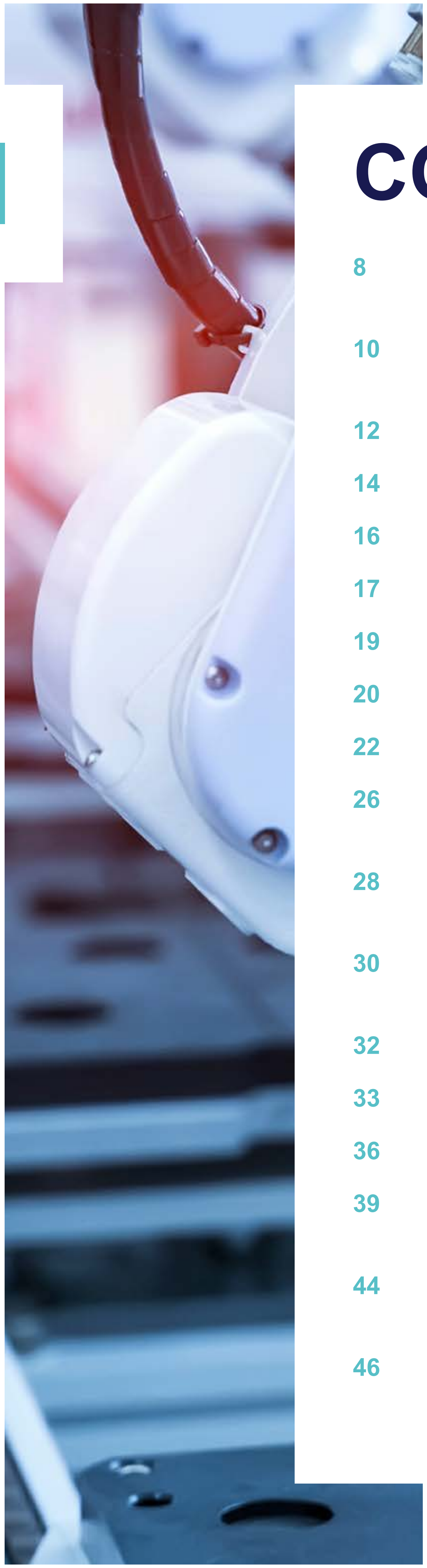
**Reduce digital manufacturing knowledge barriers**
Digital manufacturing solutions need to become as simple and intuitive to use as installing a new mobile phone app or using a self service checkout. An example of this is the no-code revolution that allows anyone to create software through more intuitive visual interfaces. This helps put the power to design flexible, scalable, customisable applications in the hands of manufacturing experts.

**Consolidate digital manufacturing guidance**
Manufacturers seeking digital manufacturing guidance are exposed to many sources of, sometimes conflicting, advice about where to start. More signposting to initiatives like Made Smarter and Knowledge Transfer Network is needed to help manufacturers access the expertise required to implement digital manufacturing solutions.

**Support employee wellbeing during transition**
Digitisation may lead to employee anxiety from the uncertainty of future job security and demand for reskilling. Communicating clearly and consistently with employees about how the opportunities digitisation offers them can help people engage with the digital transformation and not be left behind.

**Transparency of value chain data**
To enable many digital manufacturing solutions will require transparency of supply chain data (e.g. emissions). Support to improve data sharing and transparency is needed to understand the environmental and social impact of manufacturing decisions, to drive more sustainable choices.

**Figure 1**
Cross-cutting recommendations to improve the use of digital manufacturing to meet the challenges leading up to 2050



# CONTENTS



# 1. INTRODUCTION

## The manufacturing sector is the economic engine of the UK, and its source of innovation, wealth and prosperity.

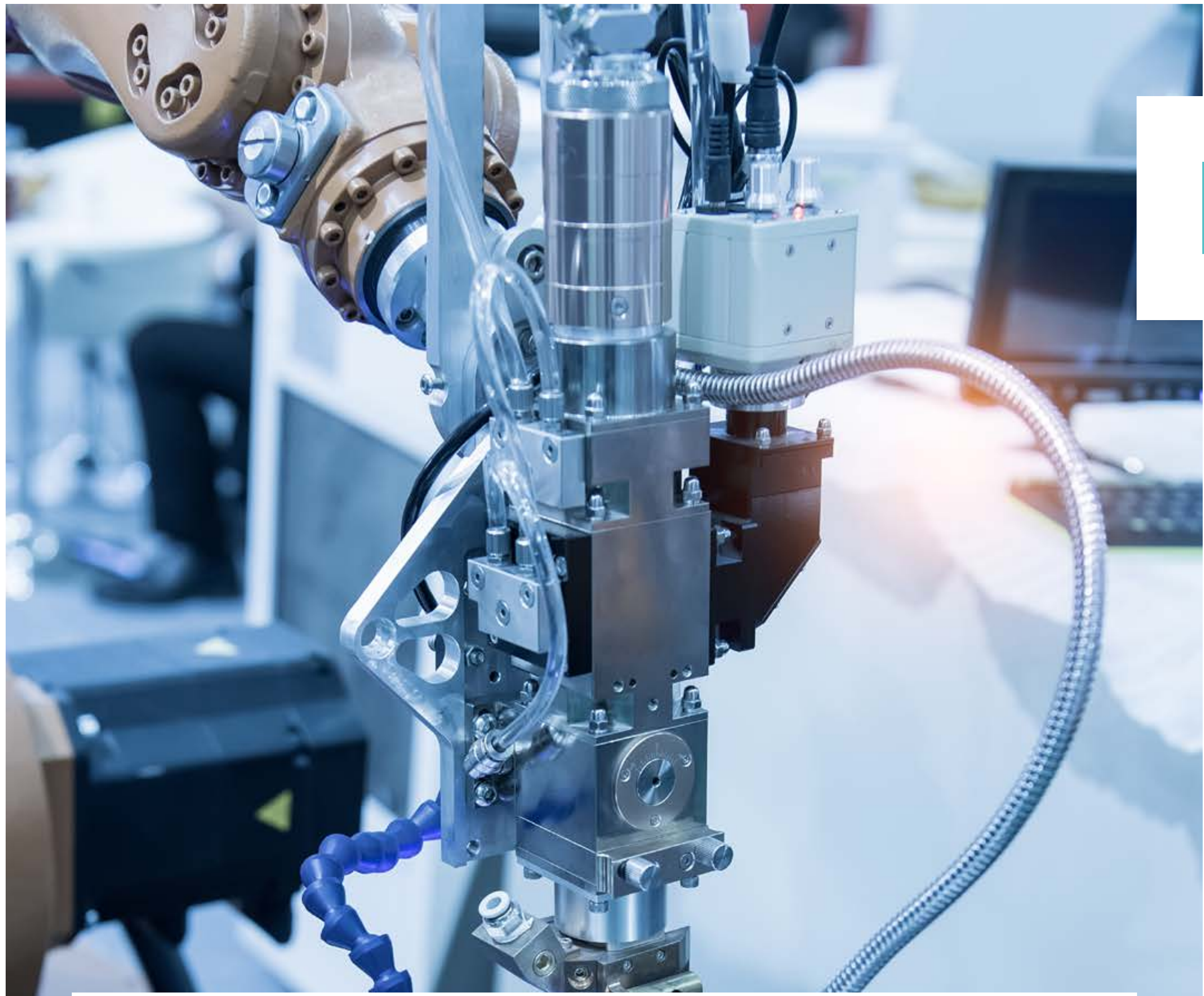
Manufacturing directly accounts 9% of the country's gross domestic product, however, this rises to 15% and 23% when considering the indirect (e.g. supply chains) and induced (e.g. spending by manufacturing employees) respective impacts [1]. Manufacturing is no longer just about production, it is a much wider set of activities that create value for the UK and benefits for wider society.

Innovation is a key driver of economic growth and improvements to living standards, through the development of new ideas, products and processes and their adoption and diffusion across the economy. In the last few years, the economic environment in which manufacturers are now operating in has dramatically changed. With seismic changes in the UK economy's situation following the UK's exit from the European Union (EU), global pandemic and war in Ukraine. This poses risks to innovation by shifting resources towards protecting against the uncertainty of the immediate future rather than taking on risks that may better society and the UK's growth. The manufacturing sector must be forward thinking, bold, and innovative if the UK is to remain one of the world's leading manufacturing nations.

The digitisation of manufacturing heralds a revolution that has undeniable implications for the manufacturing sector and wider society. The 'digitisation of manufacturing' is also commonly termed the 'fourth industrial revolution'. It refers to the use of digital technologies, data and applications to deliver advancements in manufacturing-related operations (including the broader value chain of manufacturing activities), to enhance the performance of manufactured products (and related services) in both established and emerging sectors. These digital technologies each bring significant new capabilities, but their real potential lies in their convergence and connectivity, with innovative firms identifying new business models and new ways to disrupt established ways of working. Such extensive and potential disruption requires industry and governments to plan and prepare for radical change.


**Figure 1.1**
Connected Everything's Thematic Areas





As digital technology advances, the manufacturing sector must adapt and respond to a great number of drivers and barriers. Connected Everything is an Engineering and Physical Science Research Council (EPSRC) funded Network Plus that aims to accelerate digitisation of the UK's manufacturing sector. This network supports multi-disciplinary collaboration, foster new collaborations between industry and academia and tackle emerging challenges which will underpin the UK academic community's research in support of people, technologies, products and systems for digital manufacturing. Connected Everything focuses our research through multidisciplinary thematic areas (**Figure 1.1**) that which bring together different disciplines to develop collaborative working practices and encourage discussion and information sharing resulting in improved insight into the challenges associated with industrial systems in a digital age.

Connected Everything activities aim to have specific influence on policy and society more generally through understanding the specific opportunities for UK industry and academia within a rapidly changing international landscape. For example, Connected Everything played a leading role in informing the research challenges incorporated into the 'Made Smarter' Wave 3 bid to the Industrial Strategy Challenge Fund. Manufacturing in 2050 will look very different from today, and will be virtually unrecognisable from that of 30 years ago. Connected Everything has embarked on horizon scanning activities, undertaken in collaboration with industrial partners and policy makers, to generate new knowledge on the challenges and opportunities for Digital Manufacturing practice and policy in 10, 20 and 30 years' time. This report presents the outputs from this horizon scanning study, which will help industry identify suitable collaboration partners for future research, and determine opportunities for investment in new technologies.

# 2. METHODOLOGY

This study follows the UK government foresight methodology that takes big, cross-cutting themes, summarises the evidence, and explores future possibilities.

Cross-cutting themes are additional areas that intersect with the main project (i.e. what will manufacturing look like in 2050?) and can be easily integrated into the project without losing focus of the main goal. Responses from a survey sent to Connected Everything's 500+ members were used to identify a shortlist of cross-cutting themes that will remain of critical importance to manufacturers over the next 30 years. The Connected Everything Executive Group then reviewed and oversaw the formulation of the final cross cutting themes for investigation. The Connected Everything Executive Group membership is drawn from a wide range of institutions and disciplines and includes representatives from UKRI, Catapults, other invested initiatives (e.g. ISCF Made Smarter Challenge, Brunel Challenge). Four cross-cutting themes were identified to explore within this study:

1. **Industrial Digital Technologies in 2050:** Industrial digital technologies (e.g. robotics, machine learning, virtual reality) underpin and enable digital manufacturing. Emerging industrial digital technologies are having far-reaching implications for how we produce things, exchange information and interact across supply chains and with customers.

2. **Digitisation and The Manufacturing Workforce of the Future:** As the adoption of digitisation accelerates, the impact on the manufacturing workforce is currently uncertain. This theme aims to understand the way that this will change the fundamental nature of work, and the way that we, therefore, design the technology and systems which will enable the future workplace is key to the delivery of future safe, effective and productive workplaces.

3. **Digital Support for Achieving Net Zero Manufacturing by 2050:** The manufacturing and construction sector is the third largest sector in terms of carbon emissions. While there are many routes to net zero, digital technologies are becoming central to all modern economies and understanding how they can help manufacturers achieve net zero by 2050 is crucial.

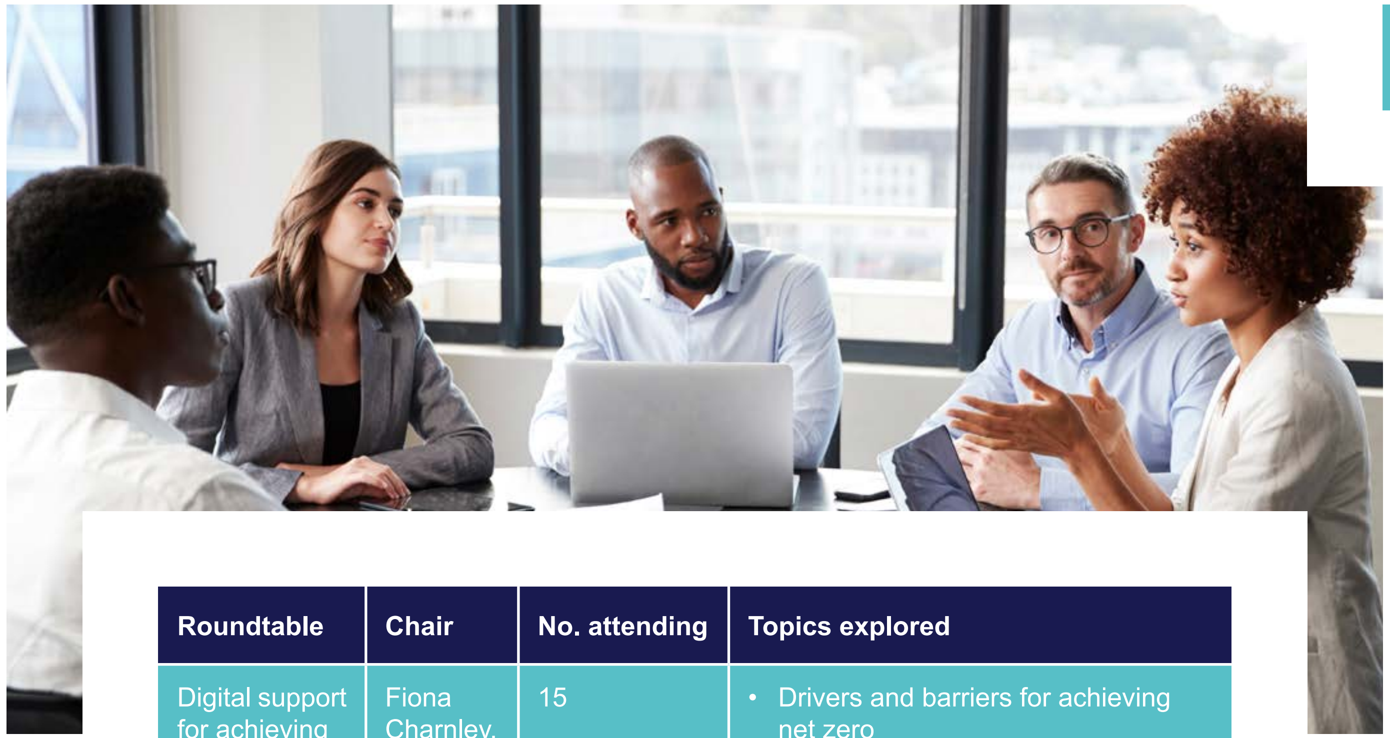
4. **Digitally Enabled Manufacturing Resilience:** Over the past two years, manufacturers have faced unprecedented disruption with the combination of the UK leaving the European Union, the global pandemic and the humanitarian disaster in Ukraine, combined with soaring transport, energy and raw material costs. This theme explored both how digitisation can play a key role in making manufacturing systems more resilient.

The study utilised three key methods as part of a framework for evidence gathering and analysis. Firstly a review of grey literature (e.g. reports, policy literature, working papers, newsletters, government documents, white papers) to understand digital manufacturing research emerging outside of traditional publishing channels. Secondly, an engaged scholarship approach to obtain the advice and perspectives of key stakeholders (in this case leaders from academia, industry and policy) to understand and solve a real-world problem. Lastly, case studies to understand current and future applications of digital manufacturing within the context of the four cross-cutting themes.

The advice and perspectives from stakeholders were acquired through several methods including: workshops at manufacturing conferences (e.g. Digital Manufacturing Week 2020, UK), survey, consolidation with Connected Everything Executive Group and a series of roundtables. The roundtables were chaired by Connected Everything investigators and invited leaders from academia, industry and policy to share their thoughts and experiences relevant to the purpose of this study. Four roundtables took place between May 2021 and January 2022. Each roundtable table address one of the cross cutting themes and conversations were focused around a set of predefined topic points, agreed by the roundtable chair, and shared with the attendees in advance of the roundtable. The roundtables are summarised in ***Table 2.1***.

A mural board for each topic area was created and used to collect data from the discussion. Connected Everything team members also recorded minutes of the discussion. Qualitative analysis of the data was then performed to draw out common themes within comments made by the roundtable participants. The findings were then shared with roundtable attendees and Connected Everything Executive Group who reviewed and validated the conclusions drawn. In addition, the results were presented and feedback provided during a workshop at the Connected Everything Annual Conference 2022, Liverpool, UK.





| Roundtable | Chair | No. attending | Topics explored |
|---|---|---|---|
| Digital support for achieving net zero manufacturing by 2050 | Fiona Charnley, | 15 | • Drivers and barriers for achieving net zero<br>• Digital support for achieving net zero<br>• Recommendations for policy, initiatives and support to achieve net zero<br>• Vision for 2050 net zero manufacturing |
| Future workforce | Sarah Sharples | 13 | • Workforce challenges<br>• Digitally related workforce challenges<br>• Digital solutions |
| Industrial digital technologies | Nik Watson | 10 | • Current and future manufacturing challenges<br>• Current and future uses of IDTs<br>• Emerging IDTs<br>• Recommendations for policy, initiatives and support to increase use of IDTs |
| Digitally enabled manufacturing resilience | Fiona Charnley | 15 | • Drivers and barriers for achieving resilience<br>• Digital support for resilience<br>• Recommendations for policy, initiatives and support to achieve net zero<br>• Risks to resilience from digital |

**Table 2.1**
Overview of roundtables topic explored

# 3. INDUSTRIAL DIGITAL TECHNOLOGIES IN 2050

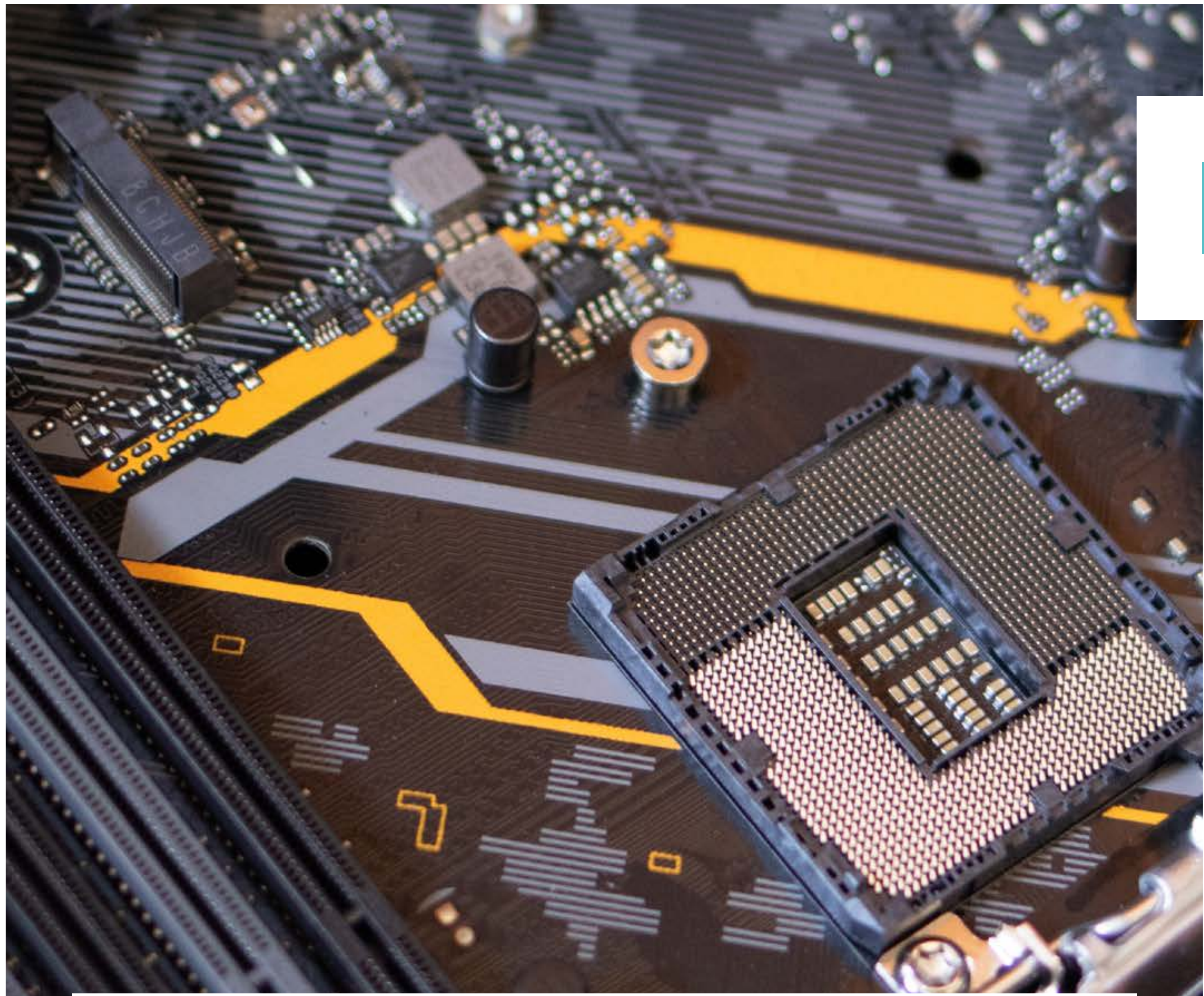
# 3.1. BACKGROUND

Digital manufacturing technologies link systems and processes across all areas of production to create an integrated approach to manufacturing, from design to production and through to the servicing of products in use.

The underlying technologies that enable digital manufacturing, or Industry 4.0, are commonly referred to as Industrial Digital Technologies (IDTs). These include robotics; automation; additive layer manufacturing; artificial intelligence and analytics; simulation; augmented and virtual reality and cloud-based platforms, as well as, emerging technologies like cobotics; human machine interaction and extended reality. The benefits of applying IDTs have been widely reported in [2–8] (**Figure 3.1**), with the most commonly referred to benefits including: reduced cost; environmental impact; and improved productivity. The Made Smarter Review, undertaken in 2017, estimated that the positive impact of faster innovation and implementation of IDTs could equate to as much as £455 billion for UK manufacturing over the next decade [3]. This could lead to a 1.5 to 3 percent increase in the growth of the manufacturing sector and a net gain of 175,000 jobs throughout the economy [3].The benefits of IDTs are not limited to manufacturing; for example, IDTs provide consumers greater transparency regarding the goods they purchase, introduce new methods of interaction with the built environment and support the wider digital economy. Furthermore, provided the implementation of IDTs within manufacturing and the wider society has been carefully considered (e.g. effect on emissions, workforce wellbeing) they may be a key part of the solution for many of the present problems facing manufacturers and society including climate change [9], water scarcity [10], food security [11] and health inequality [12].


**Figure 3.1**
Industrial digital technologies benefits extracted from [2–8]





Despite being a leader in the development of IDTs, the UK has not always been the first at adopting them. For example, while the UK is ranked 5th for digital content generation (e.g. AI scientific publications, mobile app development) the UK drops to 16th place for Future Technologies (e.g. adoption of emerging technologies and investment in emerging technologies) [13]. This may be due to the diversity of the UK manufacturing sector and the large number of small and medium sized enterprises (SMEs) that make up the UK industrial system. Make UK reports that, while larger UK manufacturers are leading technology adoption and innovation, SMEs are still not adopting IDTs at speed even though they acknowledge the benefits of doing so [14]. Initiatives like Made Smarter and the High Value Manufacturing Catapult exist in the UK to support manufacturers on their digitisation journey and appear to be making an impact in overcoming the barriers to adoption of IDTs. For example, a 2020 survey of British manufacturing companies said they had taken significant steps in adopting IDTs with some 80% confident that IDTs will be a reality in their businesses by 2025 [14].

If we are to succeed at increasing the adoption of IDTs by manufacturers, we have to ensure that the IDTs developed successfully address the future needs and requirements of the manufacturing sector. Therefore, the Industrial Digital Technologies in 2050 theme aims to investigate:

- What are the current and future manufacturing challenges?
- What new the methods for using IDTs to improve manufacturing productivity and sustainability?
- What are the emerging IDTs that offer exciting opportunities for manufacturers?
- What support and incentives are needed to speed up IDTs development and adoption?

# 3.2. MANUFACTURING CHALLENGES

The first step in designing IDT solutions is to understand what challenges manufacturers are facing now and what they will face in the future. Previous studies [15,16] have found that the biggest manufacturing challenges include:

1. Delivering the net zero/sustainability agenda
2. Supply chain disruption
3. Manufacturing workforce skills gap
4. Use of data
5. Improving productivity

During the 'Industrial Digital Technologies in 2050' Connected Everything roundtable, participants were asked to think beyond the regularly reported manufacturing challenges to identify challenges leading up to 2050. Thirteen manufacturing challenges emerged from the discussion. Six of these referred to challenges facing the manufacturing sector now and seven were challenges the roundtable participants expected to emerge in the lead up to 2050. As shown in **Figure 3.2**, these challenges fall into three categories:

- Internal challenges: Obstacles within the manufacturing business that are inhibiting growth, development of the business and/or compliance with regulations.
- External challenges: Outside actions, policy and/or events that may affect the manufacturing system and business readiness.
- Digitisation challenges: Obstacles encountered when trying to digitalise manufacturing processes or from the result of digital manufacturing

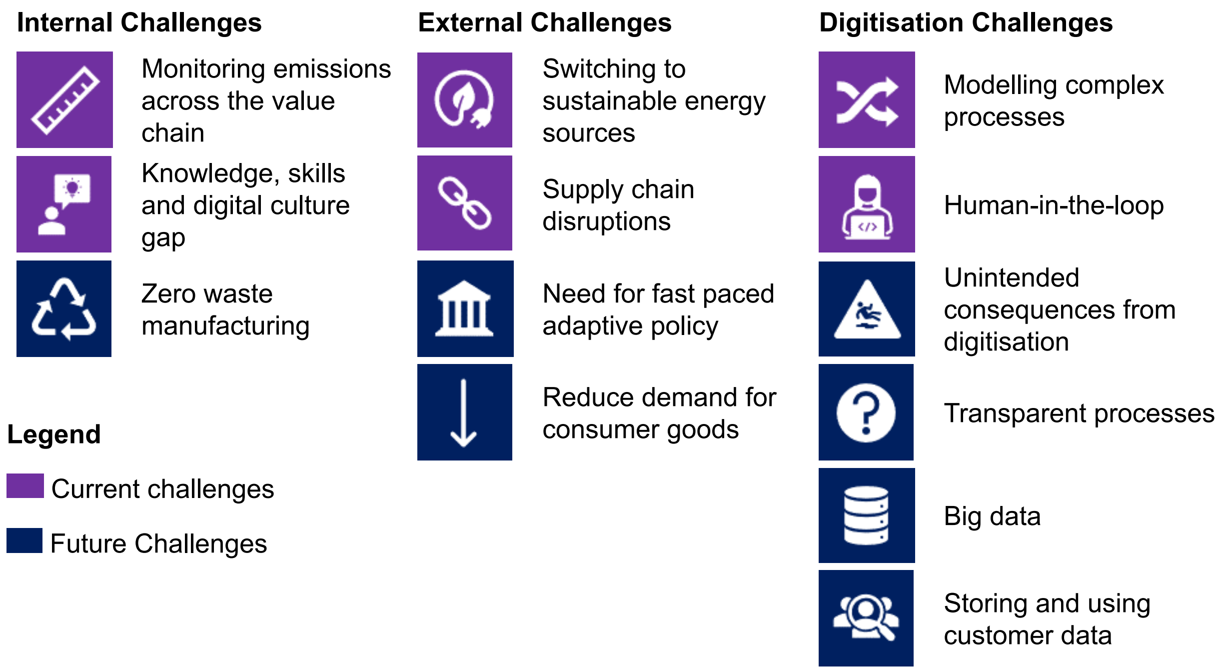



**Figure 3.2**
Manufacturing challenges identified during the Connected Everything roundtable discussion



## 3.2.1. INTERNAL CHALLENGES

### Monitoring emissions across the value chain

Manufacturers are under increasing pressure from consumers, investors and governments to reduce their emissions to limit the environmental impact of their products and processes. Before starting any decarbonisation efforts, manufacturers need to understand where emissions occur throughout the value chain, so they are able to benchmark decarbonisation efforts and identify the main contributors towards a product's emissions footprint. A product's emissions footprint can be calculated by way of life cycle analysis, which is a method used to evaluate the environmental impact of a product throughout its life cycle encompassing extraction and processing of the raw materials, manufacturing, distribution, use, recycling and final disposal. The availability of emissions data across the value chain is a major bottleneck for the widespread application of life cycle analysis. There are third-party databases that can assist manufacturers to estimate emissions from outside their organisation, however, these secondary data sources tend to be less specific and highly aggregated. In addition, secondary data also tends to be time consuming to collect. Instead, manufacturers are asking for the tools to directly measure and monitor emissions data throughout the value chain, though, this presents trust-related and technical barriers related to data sharing, as summarised in **Table 3.1**.

### Knowledge, skills and digital culture gap

The introduction of digital technologies to manufacturing has accelerated the pace of change and has brought unprecedented demands for manufacturing leaders. In addition, recent global events (e.g. demand for net zero, global pandemic, supply chain disruptions, increased customer and regulatory scrutiny) is changing the view of what manufacturers require and want digital manufacturing to deliver on. Failure to understand how to implement IDT solutions within a business and manage associated risks can result in severe financial penalties and damage a brand's reputation. Equally harmful is the failure of leadership to innovate and adopt IDTs; leading to a significant competitive disadvantage. Make UK found that a lack of willingness from management culture to change was a top-five barrier to digital transformation [14]. Organisations with a strong digital culture use digital tools and data-powered insights to drive decisions and customer-centricity while innovating and collaborating across the organisation. However, this also relies on having a digitally skilled workforce. Digital skills are evolving with technological advancements and the fast pace of change makes it challenging for manufacturing leaders to identify what skills are required within their workforce. Educational institutions will have to evolve to ensure workforce upskilling is able to keep pace. This requires providing a post-18 education system that is efficient and flexible to give workers the opportunity to study, train, retrain and upskill throughout their lives. From 2025, the UK Government will be introducing a Lifelong Loan Entitlement scheme, which is a stackable, accredited short courses to facilitate upskilling of the existing workforce as and when needed [18].

| | |
|---|---|
| **Trust-related barriers** | Fear of unintentionally giving away valuable or sensitive data about the business<br>Fear of losing negotiation power or a competitive advantage<br>Lack of visibility into data usage and analysis once shared |
| **Technical barriers** | Risk of data breaches and losses<br>Accessibility and interoperability issues that arise from combining data<br>Different digital maturity levels among participants in the same solution<br>Costs of switching technologies (or fear of technological lock-in) |

**Table 3.1**
Trust-related and technical barriers to data sharing (taken from [17])

### Zero waste manufacturing

Zero waste manufacturing is a concept to support countries' and manufacturers' transition to a circular economy by developing manufacturing technologies and systems that eliminate waste across entire value chains to the fullest extent possible through reuse, recycling and valorisation [19]. The concept challenges traditional assumptions that waste is unavoidable and has no value, by viewing waste as an 'underutilised resource' to be recovered. In 2050, emerging research suggests the concept of 'circular of design' will be predominant, where products and processes are designed to "design out waste and pollution" [20]. Looking forward, IoT platforms that enable product tracking throughout supply chains can provide a basis to incentives zero waste by rewarding sustainable product designs, utilisation and management along supply chains and across use cycles.

In assessing progress towards net zero manufacturing, data from the Office of National Statistics reveal that UK manufacturers have been able to reduce industrial waste from the 2012 peak, while still increasing industrial output (**Figure 3.3**). However, this is only one part of the manufacturers' zero waste challenge. Manufacturers produce the products we rely on every day and have an increasing responsibility, referred to as Extended Producer Responsibility (ERP), for all aspects of the products that they produce (including packaging) at all phases of the product lifecycle, including post-use. The environmental policy, which is already mandatory in France and Germany and will be shortly introduced within the UK, places the responsibility for waste disposal into manufacturers' hands, focusing on encouraging the design of new products that are easier to reuse, repair and recycle.

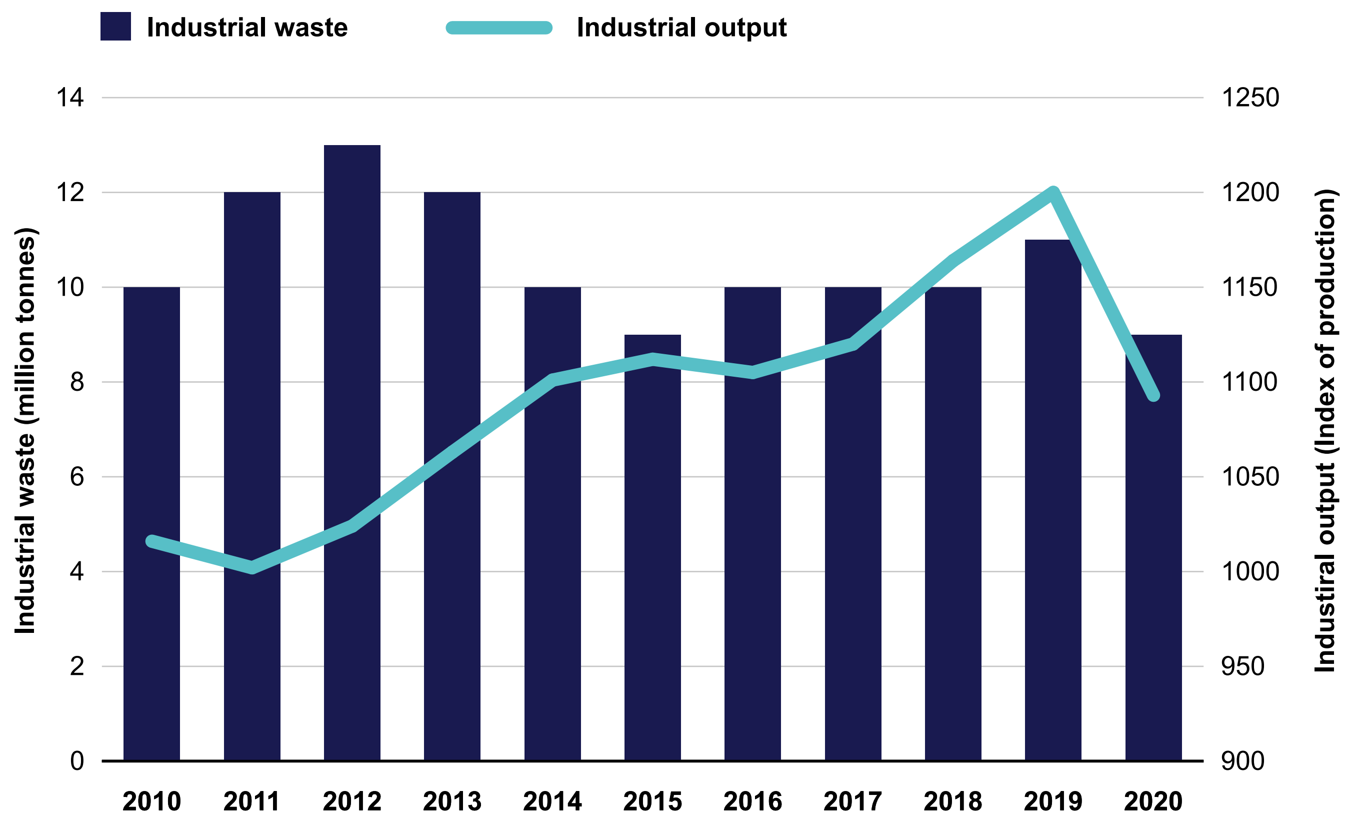



**Figure 3.3**
UK Industrial waste plotted compared to UK industrial output, data from the Office of National Statistics [21,22]

# 3.2.2. EXTERNAL CHALLENGES



### Switching to sustainable energy sources

Processing raw materials into products is one of the costliest and most energy-intensive activities within manufacturing. The energy intensity of manufacturing is greater than that of the economy as a whole. For while gross value added in manufacturing was 9% of GDP in 2021, accounting for 16% of final energy demand [23]. The good news is that renewables are increasingly becoming a more viable source for electricity generation. Renewable energy is now cheaper than fossil fuels which have risen to record prices in 2022 since the Russian invasion of Ukraine. While onshore and offshore wind and solar power all now command about £40 per megawatt, gas fired power generation costs about £140 per megawatt hour [24]. However, there are challenges for manufacturers aiming to utilise renewable energy. Variability is a key challenge for many renewable energy systems, such as wind and solar. Technological developments are urgently needed to scale up tidal, geothermal and wave power which can produce energy more consistently.

In addition, manufacturing processes are heavily reliant on natural gas for thermal energy. Hydrogen is a prime contender to replace natural gas, as the combustion of hydrogen only releases heat and water. Systems that are designed for natural gas cannot simply switch over to hydrogen without modification, as the properties of the two gases (e.g. calorific value, combustion temperature) differ too much. Trials undertaken at the NSG Pilkington St Helens facility (a glass manufacturing company), demonstrated how natural gas, normally used in the manufacturing process, can be completely replaced with hydrogen [25]. Widespread use of hydrogen is currently limited because there are almost no abundant natural sources of pure hydrogen, which means that it has to be manufactured [26]. Hydrogen can be produced through electrolysis, where electricity is used to split water into hydrogen and oxygen. Gas from this process is often referred to as 'green hydrogen' or zero carbon hydrogen when the electricity comes from renewable sources. The UK Hydrogen Strategy outlines at ambition to generate 5GW of low carbon hydrogen production capacity by 2030 [26]. The reliance of renewable energy to generate green hydrogen, which currently only accounts for around 40% of the UK energy mix, means a whole-system approach is required to developing the hydrogen economy. Looking forward to 2050, emerging research has identified the biomass and organic solid waste's conversion to hydrogen as a promising approach to a zero carbon hydrogen economy [27]. These conversion routes have the advantages of low temperature, pressure and relatively lower energy input, but are still at early stages of development. While costly to make the switch away from fossil fuel energy, moving manufacturing and other industries to renewables will provide energy stability and security over the long term.

### Supply chains disruptions

UK manufacturing is reliant on extensive international supply chains meaning that the components of many manufactured goods are imported. The recent pandemic and geopolitical events demonstrated the fragility of global supply chains, causing shortages of everyday products from computer chips to toilet paper. Future pandemics, Brexit, resource depletion, lost workforce, economic uncertainty, global conflicts, trade wars and climate change means our manufacturing processes will be subject to a greater number and frequency of unexpected disruptions. As the frequency and magnitude of disruptions increases, applying ad hoc remedies to restore predictability to a system is becoming more difficult and unsustainable. Furthermore, climate breakdown and social exclusion require may require manufacturers to reinvent the fundamental systems we depend upon, a task which requires innovation, coherence and long-term thinking. There are emerging pledges and regional commitments to address supply chain issues such as the Fab City pledge, aiming to "produce locally" by leveraging he benefits of digital technologies and localised circular economies [28].

### Need for fast paced adaptive policy

New products (across a broad spectrum of industrial sectors) will exploit several levels of technology integration and highly collaborative product development. For this to be effective requires significantly reduced quality assurance and certification timescales, as well as a more continuous process that carries on throughout the product life, though, this significantly challenges existing regulatory processes. Key to fast paced adaptive policy will be the creation of new assurance methods that not only exploit new technologies but also use more probabilistic methodologies than currently.

Current approaches to analysis and policy are heavily based on the Western scientific tradition of reductionism, where we separate complex realities into specialised disciplines, fields of research, agencies and ministries, each focused on a part of the overall truth. Systems thinking, in contrast offers a more-integrated perspective and a number of proven concepts, tools and methods to improve our understanding of the complex systemic issues which threaten the future. Thus, systems thinking can improve the prospects for successful policy outcomes and is more solutions-oriented approach, fostering transdisciplinary.

### Reduce demand for consumer goods

The United Nation Sustainable Development Goal 12 aims to promote responsible consumption and production [29]. Currently worldwide consumption and production rest on the use of the natural environment and resources in a way that continues to have destructive impacts on the planet. Should the global population reach 9.6 billion by 2050, the equivalent of almost three planets could be required to provide the natural resources needed to sustain current lifestyles [30]. While part of the solution involves reducing waste, designing circular products and replacing critical raw materials with sustainable alternatives, consumption of manufactured goods may also have to be reduced. Recently, concepts such as the sharing economy or the collaborative economy, have emerged that are the idea of socio-economic systems built around the sharing of resources. One such example is carpooling, where vehicle owners and other users share the costs related to using vehicles. Another example is clothes swapping, wherein participants exchange their valued but no longer used clothing for clothing they will use. While both these examples help reduce the environmental impact of the automobile and textile industries, they also reduce demand for the sector's respective products. Businesses that rely on customers who buy something rather than share it face a threat from businesses in the collaborative/sharing economy. Though the impact of reducing demand for manufactured products can be reduced if manufacturers switch to a product-as-a-service model.

## 3.2.3. **DIGITISATION CHALLENGES**

### Modelling complex processes

Key to digital manufacturing is the enhanced collection and use of data, which through data mining and modelling can enable evidence-based decision-making. Modelling of many physiochemical systems requires detailed scientific knowledge of the system, which is not always feasible for complex processes. Machine learning is a tool which can support data-based modelling of manufacturing processes that focuses on the development of algorithms and models that can access data and use it to learn for themselves. However, there are dangers from using machine learning methods to model complex processes (e.g. weak/misleading data, system variability not represented in the data, incorrect understanding of machine learning principals) and if not addressed such approaches can produce scientifically inconsistent results and harm trust in machine learning based models. Therefore, it is important to integrate science-based knowledge and data-based knowledge for an accurate and scientifically consistent prediction, which is sometimes referred to as science-guided machine learning. However, a lack of fundamental understanding of the manufacturing system and data regarding the sustainability and environmental impact of the manufacturing process and upstream/downstream processes, can hinder this approach.

### Misleading human–in-the-loop

Despite the rise in automation, future manufacturing systems will initially still require humans in the loop to provide a supervisory level mediation for even the most autonomous production scenarios [31]. Human-in–the-loop refers to a model that requires human interaction either to make human decisions more efficient and accurate, to make machine learning models more accurate, when the risk of prediction error is too high, or when the training data is rare or not available. The challenge of human-in-the-loop lies in identifying when to trust the human over the model and vice versa. If the model predictions reveal that operators who do not understand the fundamental process have previously operated the systems inefficiently, we need to avoid capturing the experience of these within the model.

### Unintended consequences from digitisation

When implemented correctly, digital transformation provides an opportunity for manufacturers to fundamentally change the way their systems operate. However, disruptive digital innovations can create negative externalities and unintended consequences for people, communities, industries and economies. For example, offshore windfarm installations are adversely impacting the quality of data obtained from the long-range primary surveillance radars (PSR) which are the backbone of the UK's Air Defence (AD) detection capability [32]. Manufacturers generally make offshore wind turbines out of steel. The material's reflectivity properties create "blade flashes," which produce false images on a radar's monitoring screens. Rotating turbine blades also interfere with radar systems, as the blades produce a vortex that shortens soundwaves through the Doppler effect. Technology companies are increasingly relying in other branches of research (e.g. social sciences and humanities) to better understand impacts on people, modes of working, or broader community/society [33].

### Transparent processes

As machine learning and AI models become embedded in decision-making processes, there has been discussions in research and policy communities about the extent to which individuals developing these models, or subject to a machine learning-enabled decision, are able to understand how the resulting decision-making system works [34]. Some of today's models are able to produce highly accurate results but are also highly complex. Models which produce useful information without revealing any information about their workings are known as black box models. These 'black box' models can be too complicated for even expert users to fully understand. As these systems are deployed at scale, researchers and policymakers are questioning whether accuracy at a specific task outweighs other criteria (e.g. knowledge of a systems workings) that are important in decision-making systems.

### Big data

An impact from the digitisation of manufacturing is the increasing volume of manufacturing data available. Correctly utilised new data sources are providing insights that are driving productivity and sustainability increases. However, there are challenges associated with handling and interpreting the overwhelming data volumes and varieties. The challenges from big data will grow as the manufacturing data generation rate increases with further adoption of IDTs by manufacturers. Moreover, there are growing environmental concerns associated with the storage of increasing volumes of data. Data centres alone are predicted to produce 1.9 gigatonnes, or 3.2% of the global total, of carbon emissions by 2025 [35]. The assumption that digitisation collected means automatic productivity improvements and emission reductions is a fallacy. For example, process manufacturing already collects a large amount of data from process control systems, but it is not fully utilised, often only used for emergency after the event analysis [36]. Moving forward the emphasis may shift from increasing data quantity to focusing on data quality.

### Managing and creating value from customer data

Exploiting customer data to create personalised products may give manufacturers a competitive advantage over their rivals. Indeed, research from Deloitte shows that some customers are prepared up to spend 20% extra for personalised products or services [37]. As demand grows for personalised products, how can manufacturers design and build an increasing range of products that add value to the consumer? Furthermore, with the introduction of General Data Protection Regulation (GDRP), greater scrutiny is being given to how manufacturers collect, store, use and share consumers' data [38]. A 2019 survey conducted by Cisco revealed a new group of consumers, who care about privacy, are willing to act and have done so by switching companies or providers over data or data-sharing policies. In the future manufacturers may have to balance an increasing demand for personalised products with less access to consumer data.

# 3.3. FUTURE USES OF INDUSTRIAL DIGITAL TECHNOLOGIES

Industrial digital technologies are currently used in a variety of applications to improve manufacturing economic and environmental sustainability from the automation of production lines to using additive manufacturing technology in the development of drug delivery systems.

The Connected Everything roundtable highlighted five future uses of IDTs that the participants believe will be important in addressing future manufacturing challenges (**Figure 3.4**).


**Figure 3.4**
Future applications of industrial digital technologies



## Large scale systems modelling

The adoption of digital technologies in manufacturing has enabled a wide range of new solutions for the historical evaluation and control of manufacturing systems. For enterprises to remain competitive, analysing manufacturing activities and designing systems to address emergent needs, in a timely and efficient manner, is understood to be crucial. However, existing analysis and modelling approaches adopt a narrow focus on either managerial or engineering aspects and neglect to consider the wider manufacturing ecosystems. Instead, digital technologies could enable a whole system approach to address wider economic, social and environmental manufacturing challenges. For example, the Royal Society outline how a digital twin scaled across sectors and to a global level could be developed to create a control loop for the planet to address the net zero [39]. This would work through creating digital twins deployed on a local level (individual manufacturing processes) that will be fed into whole-system modelling, helping to identify new optimisation opportunities. Importantly, system-wide control loops would bring a greater understanding of the implications of new practices deployed on a very large scale.

## Sensors to measure key variables

The advances of two industrial digital technologies, sensors and machine learning, present manufacturers with affordable methods to collect and analyse manufacturing data and enable enhanced, evidence-based decision making. These technologies will enable manufacturers to reduce their environmental impact by making processes more flexible and efficient in terms of how they manage their resources. The expected rise in the industrial deployment of sensors is driven by several factors; they are considerably cheaper than other IDTs (e.g. robots) and can often be retrofitted onto existing equipment reducing disruption to existing manufacturing processes. Historically, the main sensors that are used in manufacturing processes monitor simple properties such as temperature, pressure, flow rate and fill level. Although these are essential for process monitoring and control, more advanced sensing technologies are required to provide detailed information on manufacturing processes and key material properties. While many simple sensors exist, such as those for temperature and pressure measurements, there is a shortage of solutions for cost-effective, advanced technologies which can provide actionable information on the properties of materials streams (e.g. feedstocks, products and waste) and the manufacturing processes. Data mining and machine learning techniques may be used to analyse sensor measurements and generate actionable information. Increasingly the combination of low-cost digital sensors and machine learning to create ‘intelligent’ sensors will be used to predict key variables and provide a greater real-time understanding of manufacturing processes.

## Simple and explainable AI

Deep learning is a type of machine learning based on artificial neural networks in which multiple layers of processing are used to extract progressively higher-level features from data. Due to deep learning models’ ability to often outperform traditional machine learning methods, in terms of prediction accuracy and feature extraction, it has been the focus of recent machine learning research (**Figure 3.5**).

## Case Study 1: Virtual Production at Umlaut

**Project Partners:** Umlaut (Part of Accenture)

**Background**
Many companies face outdated, only partially digitized lifecycle processes with limited visualisation options. Missing data, no updating of data sets, a lack of links between interdependent processes, and even missing knowledge transfer of process partners increase the challenge of keeping up with the competition.

**Outcomes**
Cost savings, quality improvement, enhanced transparency by digital visualisation of process-chains, reduction of learning-curves, enhanced training solutions, collaborative planning platform for all stakeholders, process-flow optimisation, better decision-making through VR/AR representations of the product and its lifecycle, and hyper-realistic visualisation enables significantly more effective and impressive marketing.

**Digital Manufacturing Application**
Umlaut has created a digital twin based on hyper-realistic visualisation. Digital twinning and hyper-realistic visualisation are a powerful combination for industrial companies. Going beyond existing visualisation methods like CAD programs and integrating multi-layer data enables a wide range of stakeholders to test, check, improve, and optimise their processes. By digitising the whole process from concept via engineering to manufacturing & aftersales, each step gets more efficient and business more reliable. At the same time, wrong decisions are detected early, planning flaws are reduced, and costs are saved.

According to McKinsey, deep learning models have the potential to create between $1-2 trillion annually in supply-chain management and manufacturing [40].

However, the data requirements for deep learning are substantially greater than for other machine learning models. Most current manufacturing machine learning models are trained through "supervised learning", which requires data to be labelled to determine its class for classification models or value for regression models. Often labelling is completed by humans, which can be extremely costly in terms of time and disruptions to production processes. Labelling of data is one of the primary challenges with utilising machine learning methods within production environments. The data requirements mean that despite the higher accuracy of these deep learning models, they are often out of reach for many manufacturers and organisations. Therefore, more focus should be given to developing techniques to effectively manage and understand the uncertainty from fewer data-intensive machine learning models, which are suitable to meet many of the industry needs and are the best option to speed up the deployment of machine learning across manufacturing. Ultimately, the value of models is not to be found in the models themselves, but in manufacturers' abilities to harness them [41].

## Mass personalisation

Over the last decades, consumers have had increasing opportunities to customise their products and services, for instance, mobile phones and vehicles. In the future, individualised customisation, or personalisation, will become more prevalent in other sectors of manufacturing, as manufacturers continue to personalise everyday products from pharmaceuticals to specialised foods. This level of personalisation has been hard to achieve at scale, however, digital technologies are changing this. For example, while online configuration has existed for years, consumer choice has been limited to selecting between a few configuration options (e.g. giving users opportunities to choose different vehicle colours, seats and accessories or frozen yoghurt with custom topping choice). Advances in product visualisation and increased speed and adaptiveness of configured software have made customisation easier and more engaging for consumers [42]. Further advancements in digital manufacturing technologies will enable more profound changes in the product architecture, thus more products will be the subject of mass personalisation and personalisation will get more affordable. The manufacturing automation envisioned via smart factories must be supported by design automation to truly enable personalisation with mass efficiency. In the future, mass personalisation will help manufacturers increase economic and environmental sustainability by allowing them to gain a competitive advantage and reducing waste through on-demand production.

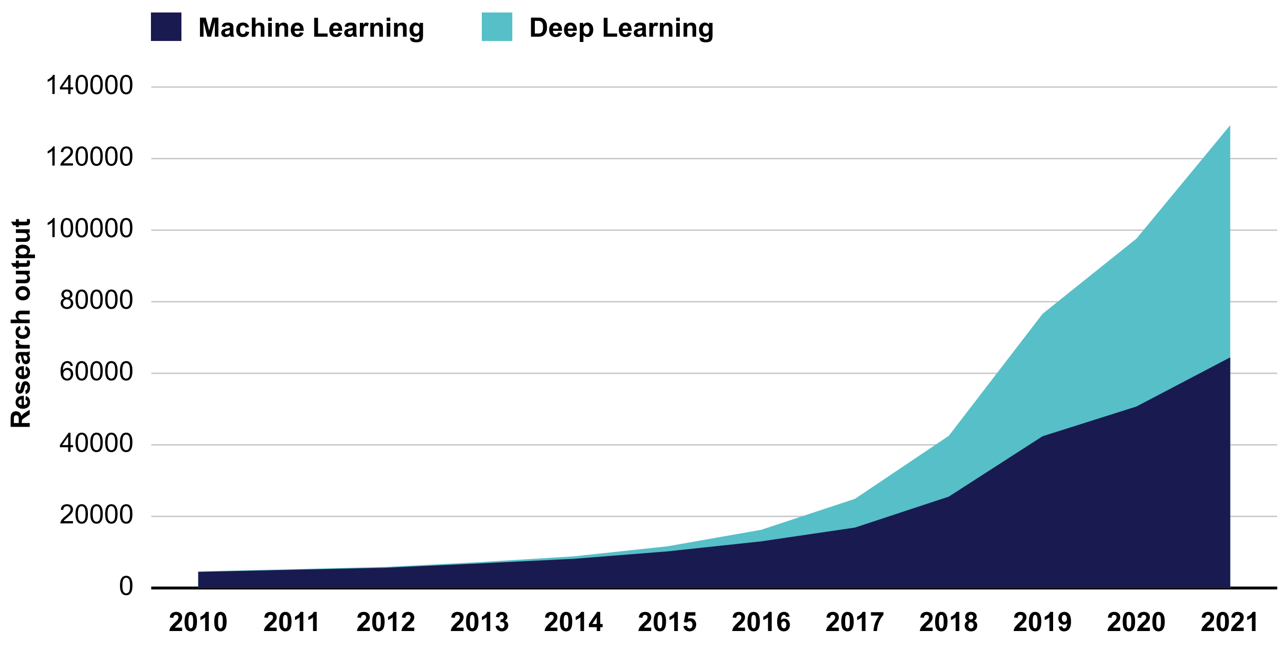



**Figure 3.5**
Deep learning vs machine learning research output [data from Scopus database 2022]

## Case Study 2: Factory of the Future

**Project Partners:** Siemens

**Background**
The Siemens' Congleton manufactures industrial drives for applications such as airport conveyor systems and they export 98% of the products they make to 78 different countries worldwide. One of the major challenges facing the Siemens is the rapidly changing demands of their customers. In recent years, the market has set expectations of mass customisation, requiring individually tailored solutions.

**Digital Manufacturing Application**
Siemens has embarked on 'virtualisation' of the Congleton site, creating a live digital replica of their facilities to better optimise its layout and understand its performance. The Visionary Render solution enables Siemens Congleton to have at their fingertips a realistic 1:1 scale virtual model of their evolving new products, manufacturing work cells and even their complete production environment. This enables all stakeholders to experience a virtual version of products as they are being developed, or all or part of the current or proposed future, production facility. Having this enterprise platform available as part of the digitisation of the Congleton factory enables teams to collaborate together more effectively and communicate clearly using a common visual language.

**Outcomes**
Factory of the Future' and lean methods incorporating immersive visualisation has resulted in £300,000 savings in just one plant optimisation case, halved product time to market, £16,000 saving per cell, or nearly £100,000 annually, reduction in work cell lead time from 13 to 9 weeks, reduction from an average of 50 issues down to 9, per new work cell.

## Reprogrammable production lines

Demand for mass personalisation and interruptions to global supply lines means production lines must become adaptable to respond quickly to changing customer and market demands. Robotics has helped automate manufacturing production lines being used for (1) material handling, (2) processing operations and (3) assembly and inspection. Conventional robotics automation tends to be fixed and specifically designed to manufacture a single or limited number of products in large volumes. However, this does not support future manufacturing demands. Whilst physical reconfiguration (i.e., the positioning of robots and process systems) is relatively easy to achieve, the major barrier is the need for time consuming and costly reprogramming to support each change. Research is supporting a more holistic view of the reconfiguration process and developing new algorithms that can automatically generate program and configuration data from CAD and process data, eliminating the need for significant human input [43]. Furthermore, future systems will also consider safety and how to automatically configure the safety system so that it is safe and legally compliant but also implement a flexible framework that allows the active intervention of human operators.

# 3.4. EMERGING INDUSTRIAL DIGITAL TECHNOLOGIES AND TRENDS

The 10th-anniversary edition of the World Economic Forum's Top 10 Emerging Technologies Report lists new technologies poised to impact the world in the next three to five years. The technologies on the list, curated by experts convened by the World Economic Forum and Scientific American, include crops that self-fertilise, breath sensors that diagnose diseases, on-demand drug manufacturing and houses printed with local materials. The Connected Everything roundtable asked the participants to undergo a similar exercise to identify the emerging technologies they believed will have the biggest impact on manufacturing over the next 10 20 and 30 years (**Figure 3.6**).

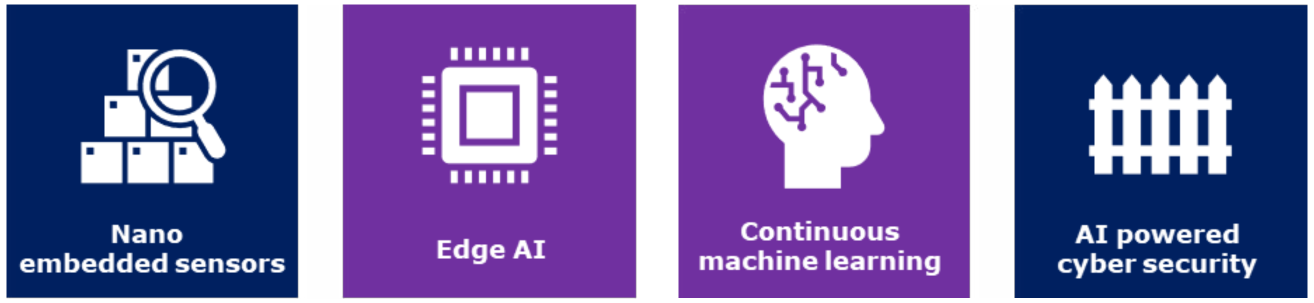



**Figure 3.6**
Four emerging industrial digital technologies that will impact manufacturing over the next 10, 20 and 30 years

## Nano embedded sensors

Embedded sensors are a type of sensor that is implanted within the environment it is sensing. Embedded sensors can work together within a network, which allows the sensors to cooperate with each other, monitor the surrounding environment and produce the appropriate response. For example, within a smart watch there are multiple embedded sensors (e.g. accelerometer, gyroscope, heart rate monitor, oximetry sensor and GPS) that monitor a user's performance during exercise and use this information to develop fitness plans. As well as embedding sensors within manufacturing products, embedded sensors provide value throughout the manufacturing value chain by enhancing industry process control, supply chain and logistics, real-time inventory tracking, driving operational efficiencies, automation and production lines to meet consumer demand and facilitate adherence to regulatory compliance. Advances in nanoscale embedded sensors provide new non-destructive, in-situ means to monitor material properties. Nano sensors are a sub-class of nanomaterials that are sensitive in some way to their local environment, and thereby allow for the detection of key properties of the material or its surroundings at sub-micron length scales. Nano-embedded sensors offer several advantages over their microscale counterparts, including lower power consumption, fast response time, high sensitivity, lower concentration of analytes and smaller interaction distance between sensors and products.

## Edge AI

The overwhelming volume of manufacturing data presents modelling challenges. For example, the multitude of sensors and devices in a large oil refinery generates one TB of raw data per day [44]. Sending all this raw data back to a private server for storage or processing would require considerable bandwidth, availability and power consumption. In many industrial applications, especially highly distributed systems located in remote areas, constantly sending large amounts of data to a central server is not possible. Edge computing allows sensor-enabled devices to collect and process data locally to deliver insights on the factory floor without having to communicate with the cloud. Edge AI enables any device or computer to process data and make AI-led decisions in real time, with minimal latency. There are several advantages:

- Significantly reduces latency, enhancing the real-time decision-making capabilities.
- It increases the level of security in terms of data privacy through local processing. Data is no longer shared in a centralised cloud.
- Decentralisation of the processing makes all the distributed systems efficient and self-sustained.

## Continuous machine learning

As machine learning's use in manufacturing becomes more common, the tools and best practices to make the most out of machine learning will have to become more sophisticated. One of the main limitations with machine learning is the models, without re-training, will become outdated due to changes to the manufacturing system over time. A model built based on historical data can become stagnant. In many cases, new manufacturing data is being continuously generated as the manufacturing system evolves (i.e., new variations, new patterns, new trends), which the historical data does not capture. Online machine learning is a method in which models continue to learn as data becomes available by using the new data to retrain the best model predictor for future data at each step. While not a new technique, online machine learning use within manufacturers is not extensive.

Online learning algorithms may be prone to catastrophic interference, which is the tendency of models to completely and abruptly forget previously learned information upon learning new information. This is a danger for many manufacturing applications of machine learning. For example, a model aimed at predicting different unsafe events may forget what certain events look like within the data if the occurrence of these events are rare. Multi-agent machine learning, where a mixture of models, or 'experts', are trained to remember key events could ensure these events are not forgotten as the models continue to train new models with new data.

## AI powered cyber security

Sophisticated cyber-attacks on manufacturing systems are becoming more frequent, resulting in the need for advanced cyber-security systems. It is estimated that, worldwide, cyber-attacks will cost $10.5 trillion annually by 2025 [45]. Manufacturers are adopting new cybersecurity technologies, such as artificial intelligence, to monitor and guard networks against hackers in real-time rather than responding to the threat after the damage is already done.



To achieve AI powered cyber security, developers need access to manufacturers' datasets that contain examples of cyber-attacks so the models can learn from these experiences. However, manufacturers are naturally reluctant to release their data, particularly if it has revealed weakness in their networks. What few existing datasets are available could have the defects of old data, redundant information and unbalanced numbers of categories. Although the data can be improved after processing, there is a problem of insufficient data volume. Therefore, establishing network cyber-attack datasets with large amounts of data, wide-type coverage and balanced sample numbers of attack categories is a top priority in the field of AI powered cyber security.

### Case Study 3: Cognitive Security

**Project Partners:** Wimbledon and IBM

**Background**
Digital experience is crucial to helping grow the value of brands by attracting a new "digital native" audience, but it also increases risk from cybercrime. A key issue facing security operations today is that the volume of security incidents and available threat data far exceeds the capacity of even the most skilled security professional. Cognitive and other security technologies enabled analysts to quickly and efficiently identify and address the real threats hidden in nearly 200 million events experienced during the Wimbledon tennis tournament.

**Digital Manufacturing Application**
The Wimbledon website is protected by multiple security products, at the core of which is IBM® QRadar® SIEM, a security intelligence platform that brings together data from thousands of endpoints and devices across the infrastructure, correlates it and helps the security team prioritize and identify the threats they are facing. Combing the QRadar Advisor with IBM's AI platform, WatsonTM, an analyst is provided with a description of the threat and a recommended set of actions based on Watson's analysis of the threat.

**Outcomes**
Where it might have taken 60 minutes to analyse a security threat, with help from Watson an analyst can do it in just a minute. That 60 times increase in speed translates into being able to tackle a fivefold volume of incidents and alerts.

# 3.5. CONCLUSION AND RECOMMENDATIONS

The digital transformation of manufacturing is introducing new technologies into manufacturing processes.

Collaborative endeavours between research and industry are needed to understand how we can maximise the positive impact of these technologies to address the internal, external and digitisation challenges leading up to 2050. This theme highlighted five future uses of industrial digital technologies, as well as four emerging technologies, that can help manufacturers address these challenges.

Summary of the future uses of industrial digital technologies:

1. **Large scale modelling:** Digital technologies will enable a whole system approach to address wider economic, social and environmental manufacturing challenges. Importantly, system-wide modelling would bring a greater understanding of the implications of new practices deployed on a very large scale.
2. **Sensors to measure key variables:** Increasingly the combination of low-cost digital sensors and machine learning to create 'intelligent' sensors will be used to predict key variables and provide a greater real-time understanding of manufacturing processes.
3. **Simple and explainable AI:** The greater focus should be given to developing techniques to effectively manage and understand the uncertainty from less data intensive machine learning models. These models are suitable to meet many of the industry's needs and are the best option to speed up the deployment of machine learning across manufacturing.
4. **Mass personalisation:** Personalisation has been hard to achieve at scale, however, digital technologies are changing this. In the future, mass personalisation will help manufacturers increase economic and environmental sustainability by, gaining a competitive advantage and reducing waste through on-demand production.
5. **Reprogrammable production lines:** Future manufacturing demands require flexible and agile production lines, which the current use of automation and robotics does not support without significant human intervention. New algorithms that can automatically generate programme and configuration data from CAD and process data eliminate the need for significant human input.

Summary of the emerging industrial digital technologies:

1. **Nano embedded sensors:** Embedded sensors provide value throughout the manufacturing value chain by enhancing industry process control, supply chain and logistics, real-time inventory tracking, drive operational efficiencies, automation and production lines to meet consumer demand and facilitate adherence to regulatory compliance. Nano embedded sensors offer several advantages over their microscale counterparts, including lower power consumption, fast response time, high sensitivity, lower concentration of analytes and smaller interaction distance between sensors and products.
2. **Edge AI:** The overwhelming volume of manufacturing data makes it slow and resource intensive to send data to centralised locations for analysis and modelling. Edge AI enables any device or computer to process data and make AI-led decisions in real time, with minimal latency.
3. **Continuous machine learning:** Machine learning models need to be able to continually learn so that they keep pace with evolving manufacturing systems. Currently, online machine learning methods risk forgetting key events as they update their models with new manufacturing data. Multi-agent machine learning could ensure these events are not forgotten as expert models are built to remember these key events.
4. **AI powered cyber security:** Manufacturers are adopting new cybersecurity technologies, such as artificial intelligence, to monitor and guard networks against hackers in real-time rather than responding to the threat after the damage is already done. This will require public assess to a greater number of cyber attack databases so manufacturers have access to the data to train their AI cyber security systems.



Making industrial digital technologies easier to use and develop relies on contributions from multiple stakeholders. From the Connected Everything roundtable discussion we make four recommendations to guide industrial digital technologies' future research agendas and policy, which are summarised in **Figure 3.7**.

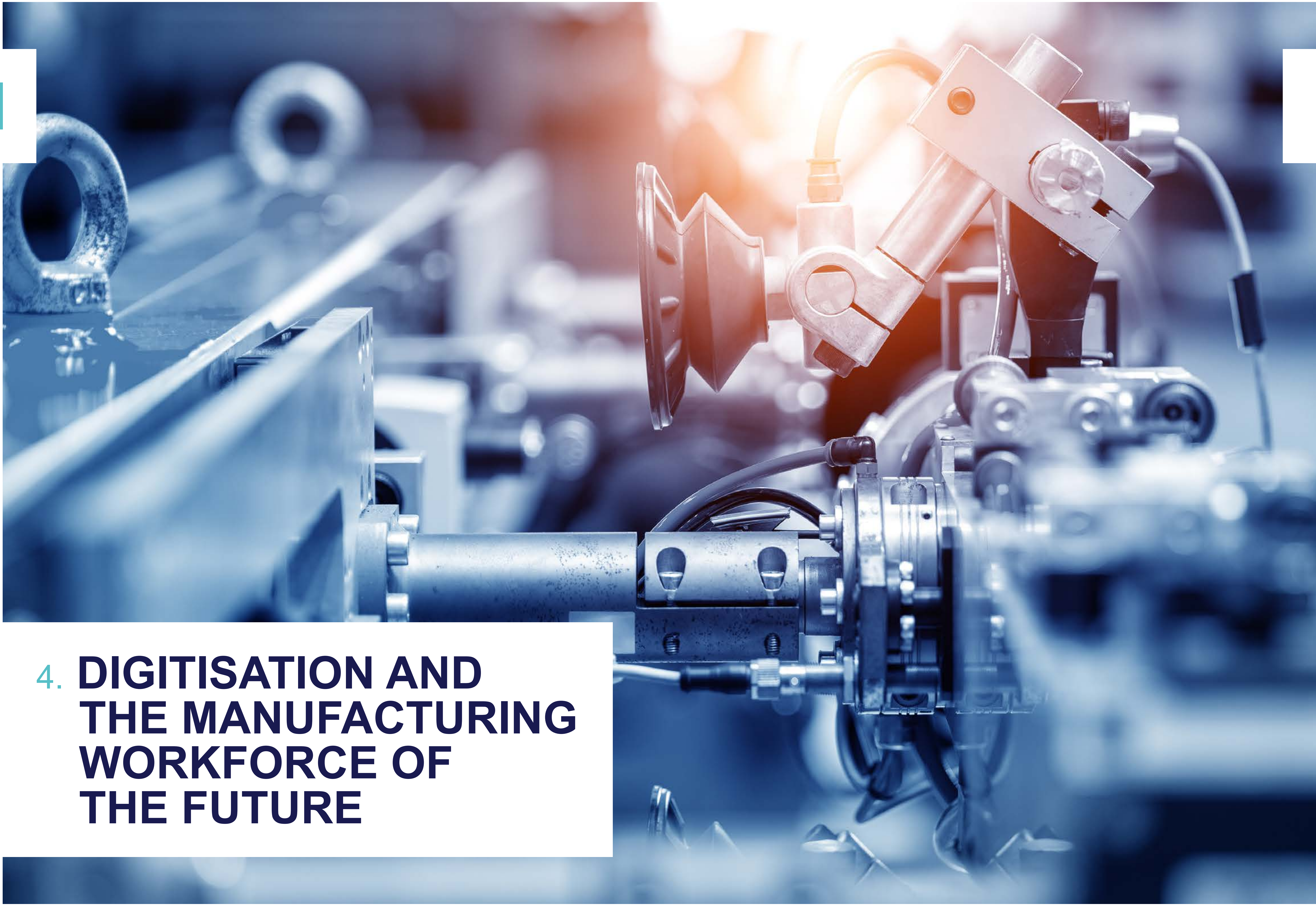
**Quantify digital solution impact**
Previous work has focused on quantifying the sector wide impact of digital manufacturing, rather than demonstrating the impact of individual digital solutions. There is a need to demonstrate the digital manufacturing cost vs benefit so the manufacturer can make informed decisions about which digital solutions to invest in. The benefits from digital manufacturing should extend beyond economic gains to include environmental and social indicators (e.g. the volume of waste reduced, emissions saved, the health of staff).

**Connect digital technology developers to manufacturers**
Greater support to connect manufacturing businesses with the UK innovation community, creating opportunities, increasing productivity and solving industry challenges. This will ensure future digital manufacturing research will develop solutions that fit manufacturing priorities.

**Reduce digital manufacturing knowledge barriers**
If we are to encourage more widespread use of industrial digital technologies, they should be made simple, like setting up a new mobile phone app or home Wi-Fi system. An example of this is the no-code revolution that allows anyone to create software through more intuitive visual interfaces. This helps put the power to design flexible, scalable, customisable applications in the hands of manufacturing experts.

**New funding processes to reflect digital research**
Funding schemes need to adapt to reflect the requirements and speed of digital research innovation. Funders should experiment with application processes to reduce burdens for applicants and speed up the funding review process, as seen during compressed application and assessment processes used for Covid-19 funding calls. In addition, new measures are required to help industry can engage with research effectively to ensure digital manufacturing research continues to meet the industry's needs.

**Figure 3.7**
Recommendations from Connected Everything roundtable discussion to support the development and use of industrial digital technologies



# 4. DIGITISATION AND THE MANUFACTURING WORKFORCE OF THE FUTURE

# 4.1. BACKGROUND

The manufacturing sector directly employs over 2.7 million people in the UK. The pandemic forced businesses to rapidly shift towards remote work, innovation and automation, enabled by the ubiquity of digital technology. As the adoption of digitisation accelerates, the impact on the manufacturing workforce is currently uncertain. Compounding the issue, 57% of companies report their organisations lack the skilled workers they need to support future digitisation initiatives [46]. Manufacturing careers are evolving to become increasingly high-tech, high-skill and high-pay. The possibilities in manufacturing will become even more exciting as digital manufacturing continues to revolutionise the sector. How can the manufacturing sector prepare for this future workplace and ready its workforce to work beside robots and advanced technologies?

Digital manufacturing offers huge potential to transform the way that we live and work. Considering the way that this will change the fundamental nature of work, and the way that we, therefore, design the technology and systems which will enable the future workplace is key to the delivery of future safe, effective and productive workplaces. Therefore, this theme aims to:

- Identify gaps in the current manufacturing workforce challenges.
- Understand what challenges digitisation presents to the workforce.
- Identify the opportunities from digital manufacturing.
- Provide recommendations to ensure the future manufacturing workforce is secure, satisfied and healthy.



# 4.2. MANUFACTURING WORKFORCE CHALLENGES

To develop a more integrated and connected approach to address future workforce challenges, we first need to understand what these challenges are.

Previous research by Connected Everything [47] and the High Value Manufacturing Catapult [48] has identified the following manufacturing workforce challenges.

1. Developing flexible people, processes and organisational systems
2. Achieving ubiquitous sensing and modelling
3. Liability, responsibility and ethics
4. Acknowledged current and future skills shortfalls
5. Ageing workforce demographics and reduced migration
6. Fragmented education and training systems
7. Rapid digitisation of manufacturing and supply chains
8. Comparatively small higher-technical skills base
9. Poor demand alignment across sectors and across technologies

During the Digitisation and The Manufacturing Workforce of the Future Connected Everything roundtable, participants were asked to identify gaps in these challenges. Twelve challenges emerged which can be split into two categories (1) manufacturing workforce challenges and (2) digitisation workforce challenges.


**Figure 4.1**
Challenges facing the manufacturing workforce identified during the Connected Everything roundtable

## Losing talent

Both the Covid-19 pandemic and the implementation of Brexit strained supply chains and shrunk the talent pool available to employers. The manufacturing industry is struggling to attract, hire and retain talent for roles ranging from skilled production workers to researchers and developers and digital manufacturing experts, to operational and business managers. Even before this latest talent shortage, however, the sector has struggled to be perceived as a desirable destination for young talent. In 2013 only 15% of secondary age students stated that they would consider a career in manufacturing and 40% of these students considered manufacturing to be boring [49]. More recently only 17% of the public knew that average earnings in manufacturing exceed the average earning of the whole UK population and people viewed UK manufacturing as ranked 56th in the world compared to its actual 9th position [50].

Digital skills are becoming more important across the economy, meaning that manufacturers are competing with cash rich sectors to attract the best digital talent into manufacturing. Attracting and retaining skilled employees requires a new approach. Manufacturers will need to create new talent development paradigms to compete for top talent, as well as implement programs to upskill or cross-skill workers who do not have the right background to build and maintain a sustainable workforce. While manufacturers must increase their attractiveness and develop more flexible ways to engage with these talents, they may think about cooperating with universities, research institutes and other companies to capture digital talent.

## Manufacturing workforce diversity

Diversity includes the representation, in a group, of various facets of identity, including (but not limited to) ability, age, gender, ethnicity, nationality, race, religion, sexual orientation and socioeconomic status. A diverse workforce experiences increased productivity and better organisation management, they have been shown to have a competitive advantage in the industry [51]. A 2021 Make UK survey of manufacturers in the UK found that only 67% of manufacturers have an equality, diversity and inclusion strategy or are planning one, just 2% of the manufacturers have an average workforce age below 30 and Minority ethnic representation on boards is only 5% [52]. A weakness of the currently manufacturing workforce knowledge is the lack of experience recorded of those with intersectional identities, across race, ethnicity, gender, class, disability and/ or LGBTQI.

Manufacturers cannot only focus on recruiting diverse talent, but must focus on building an inclusive culture, fostering growth opportunities and pathways to careers and ensuring these values reach every level of the business. As the digital transformation continues, researchers and manufacturers should ensure technologies developed by and adopted in manufacturing should be inclusive. Technologies that exclude lead to a less diverse workforce and perpetuate the cycle (**Figure 4.2**). Technologies that are created with an inclusive mindset, often have much wider benefits and can enable everyone to perform better.

## Evolving career expectations

Expectations from work and career paths are changing and the manufacturing sector needs to be ware of these expectations if it is to address the talent shortage. The 2020 Deloitte Global Human Capital Trends study identified well-being as a top trend, cited by 80% of respondents across industries [56]. The roundtable discussion highlighted five future workforce expectations that will affect manufacturers.

1. **Work is more fluid:** The pandemic has made work a more fluid concept. The regimented 9 to 5, Monday to Friday working week is now less common with technology is blurring the borders between home and work.
2. **Future workforce will have multiple parallel career paths:** Projects quickly flourish, evolve and resolve and specialists move rapidly from one to the next. Future graduates are expected to have five plus careers [57].
3. **Workers are environmental, social and governance aware:** Workers will be attracted by the opportunity to work for an organisation they admire and whose values align with their own.
4. **Value on quality of work:** Workers are more aware of the impact low-quality work can have on their health and are prioritising work quality over other work benefits.
5. **Workers are attracted to work at technology advance companies:** Younger workers are attached to work at the cutting edge of the industry and want to be involved in the development and deployment of new technologies. However, while meaningful work may be desired consistently across social status groups, socioeconomic privilege may play a significant role in one's ability to access desirable jobs



**AI and Machine Learning**
When AI applications are trained with unrepresentative datasets, AI can risk increasing inequality by reproducing or exacerbating the marginalisation of historically disadvantaged groups. For example, AI-powered tools that are used to recruit, hire and promote workers can reflect race, gender and ablism biases, reproducing past patterns of discrimination and exclusion [53]. This is due to the less data on underrepresented groups being available, meaning the AI model may evaluate future applicants as unlikely to be a good fit for the company.

**Robotics and Automation**
Robotics and automation have the potential to displace jobs, which may disproportionately affect one part of the population, while creating new jobs for other parts of the population. The World Economic Forum warns that on current trends, women will lose out in an automated economy because they are underrepresented in jobs that are expected to expand and command higher wages [54]. Therefore, we need to focus on creating pipeline into these new jobs that is accessible to everyone.

**Figure 4.2**
Examples of digital technology development where equality, diversity and inclusion has not been considered[55].

## Integrating workforce needs within industry strategy

Industry, academia and government have a collective accountability to build a workforce fit for the future. Leaders in industry and innovation need to work together to provide a long-term vision of the manufacturing skills (technical and soft skills) needs and communicate this effectively to partners in education, training and government. There needs to be a clear mechanism to bring these partners together to develop a coherent workforce strategy that is integrated into the national industrial strategy. This should go beyond just skills, which is the current focus of the national strategy, to address wider manufacturing challenges such as diversity and evolving workforce expectations. Work by the High Value Manufacturing Catapult outlines over 40 international good practice examples that the UK can learn from when developing a national manufacturing workforce strategy [48]. Part of this solution is moving towards a talent based workforce, rather than a qualification based workforce, ensuring the workforce is equipped to tackle future challenges.

## Balancing current and future workforce requirements

There is a danger of overly focusing on the future workforce at the expense of the current workforce, as 80% of the future workforce is already employed. Make UK reports that two-thirds of manufacturers survey lack confidence that vocational training is keeping pace with the digital skills they need now [58]. Upskilling the current workforce is a priority for manufacturers. To address the immediate term manufacturing workforce challenges, Make UK are calling on Government to establish a National Skills Taskforce with the aims to match skilled workers with manufacturers, support workers to identify new opportunities where their skills are in demand and develop a national upskilling programme.

## Ensuring the right skills are in future workforce

An accelerating pace of change drives the need to act proactively to ensure that the UK's manufacturing industry has a workforce with the right skills, when and where they are required. With the acceleration of the digital transformation, the World Economic Forum estimates that by 2025, 50% of workers will need reskilling because automation will displace 85 million jobs worldwide, while 97 million new roles will emerge adapted to fill business digital capabilities needs [59]. Furthermore, a separate report by the World Economic Forum estimates that 65% of children will be employed in jobs that do not yet exist [60]. The pace of change makes it very challenging for workers to understand both what job roles are in demand and what skills are most valued by industry.

The new workers need to be flexible, work on demand and bring skills to bear as and when they are required. Modern manufacturing workers not only need to be adept at the traditional manufacturing technologies but also ought to be trained in advanced data-rich computer-automated technologies and soft skill (e.g. creative thinking). A traditional UK university's curriculum often centres on the distinct subject matter taught through siloed academic disciplines. Digital technologies innovations are happening across disciplines and workers will need to be able to collaborate with other disciplines to produce new knowledge and practical solutions within manufacturing. Furthermore, an interdisciplinary environment does not only cover the interaction between humans, but includes interaction between humans and technology. There are learnings to be taken from other countries that have boarded universities degrees, for example, France where engineering degrees includes philosophy. Universities should perceive interdisciplinarity as a crucial competency that students need to acquire and develop in order to function effectively within the manufacturing workforce.

# 4.3. DIGITISATION WORKFORCE CHALLENGES

The digital manufacturing transformation is creating specific challenges for the workforce.

The human aspect is a key element that organisations should manage properly for the successful transition and implementation of digitisation. Even though digitisation has many benefits for the workforce in terms of reducing repetitive tasks, minimising errors and increasing the quality of production, potential disruption in the current workforce and changes in expectations may trigger the concerns of both manufacturers and workers [61].


**Figure 4.3**
Challenges facing the manufacturing workforce as a result from digitisation



## Delivering productivity gains

To maximise the positive economic, environmental and social impacts of digital manufacturing, manufacturers need digital skilled workers within their workforce. However, manufacturers are struggling to attract digital skilled workers into manufacturing. In order to enhance these key workers, manufacturers need digital manufacturing to significantly improve productivity so they can offer larger awarders for digitally skilled workers. This is creating a vicious cycle (Figure 4.4), which is stalling the digital manufacturing transformation.

As digital transformation redefines manufacturing jobs, leaders and workers alike need to embrace a work environment that can blend advanced technology and digital ability with uniquely human skills for the highest level of productivity.

## Loss of skills and manufacturing knowledge

There is a danger that the drive to increase digital skills within the manufacturing workforce may be at the expense of other skills (e.g. core psychomotor skills) and knowledge vital for manufacturing. These lost skills and fundamental machining/manufacturing knowledge may still be required for elements of 'leftover automation' and in specialist settings. For example, the UK has only one traditional sievewrigth trading in the country that now provides specialised personalised products to meet industry needs [62].

Overly focusing on digital skills will not address the wider manufacturing challenges (e.g. net zero, social progression). Instead, soft skills like critical thinking, problem solving and social flexibility will determine whether tomorrow's manufacturing workforce can better understand the social opportunities from digital manufacturing. Future advanced manufacturing workforce will have to master a more complex and changing mix of technological knowledge, an increasing range of skills and some new behaviours to successfully deploy emerging technologies.

## Developing new sustainable business models

Digital transformation is not just about embracing new technology; it is about a change in thought and organisation culture. There is a need for organisations to address the change in business scenarios and dynamic business demands and to innovate ways to quickly cater to these changing needs. Thus, digital transformation is about accelerating business activities, lowering costs, improving time to market and bringing about a positive change in processes, people and competency models. Value creation is increasingly shifting from production to data-based services. Platforms play an increasingly important role in the orchestration of processes and business partners. The corresponding exponential increase in the importance of data and services in value creation forces companies to critically reflect on their traditional business models and assess their future viability.

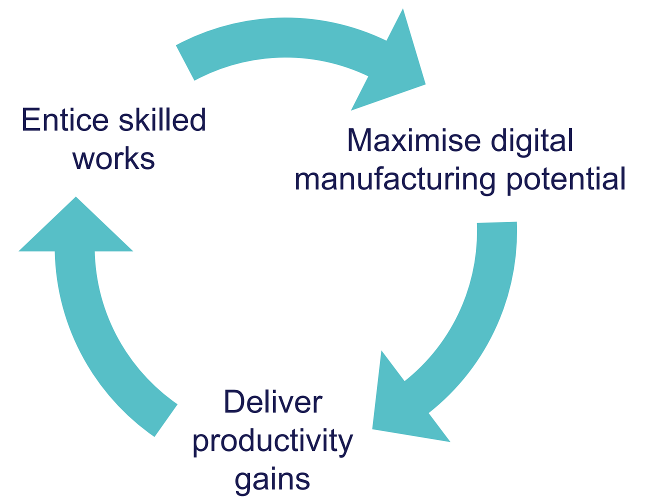



**Figure 4.5**
Digital manufacturing's vicious virtuous cycle

Grand challenges around climate change, poverty reduction, food security, biodiversity, sustainable consumption and equality are forcing manufacturers to radically alter their business models to become more sustainable. However, there are opinions that firms need to go far further than current initiatives, such as net-zero and circular economy, and aim to deliver meaningful net-positive environmental and social value. The new terminology of "regenerative business models" is an aspirational type, whereby the industry actively seeks to rectify the environmental (and societal) damage done over the past decades of economically driven manufacturing [63]. Combining the impact of digitisation on how businesses operate with a need for a more sustainable business model is both a challenge and opportunity for manufacturers.

## Connecting digital solutions developers to manufacturers

The pace of the digital manufacturing transformation has been slower than some expected. Part of the problem is that digital manufacturing researchers and innovators do not understand the priorities of manufacturers. This can lead to the development of digital solutions that manufacturers are not asking for or which require a digital maturity beyond their current reach. While we do not want to stifle novel and future facing innovation, we do need also to implement practical solutions. Therefore, the development of pathways to link digital solution developers to manufacturers are needed to support collaboration. To increase digital manufacturing impact, we need to get the right people at the right time, using the right technology.

### Digital maturity imbalance

Variability in the digital maturity and skills across the value chain and between sectors is limiting digital manufacturing's full potential (e.g. system-wide modelling of real-time data). Within manufacturing, a high level of diversity exists across various industry sectors. The Smart Industry Readiness Index (SIRI) is a global measure for digital transformation maturity, which helps to increase awareness and set targets that organisations can work towards [64]. The 2022 World Economic Forum uses this measure to report that the semiconductor, electronics and pharmaceutical sectors are frontrunners in digital transformation [65].

Governments and solution providers tend to apply "one-size-fits-all" approaches in supporting manufacturers on their digitisation journeys, whereas, more tailored approaches are required to better support specific industry digital transformation. This can be supported by insights from the SIRI insights, as they can help institutions to conceptualise and implement sector-specific, targeted interventions that maximise both efficacy and impact.

### Knowledge to apply digital solutions correctly

When implemented correctly, digital transformation provides an opportunity for manufacturers to fundamentally change the way their systems operate. However, disruptive digital innovations can create negative externalities and unintended consequences for people, communities, industries and economies. Research from McKinsey shows that only 16% of respondents say their organisations' digital transformations have successfully improved performance and also equipped them to sustain changes in the long term [66]. This gets worse in more traditional industries, such as oil and gas, automotive, infrastructure and pharmaceuticals, where digital transformations are even more challenging: success rates fall between 4-11% [66]. Five ways to improve success include:

- Having the right, digital enabled leaders in place.
- Building capabilities for the workforce of the future.
- Empowering people to work in new ways.
- Giving day-to-day tools a digital upgrade.
- Communicating frequently via traditional and digital methods.



# 4.4. MANUFACTURING WORKFORCE OPPORTUNITIES FROM DIGITISATION

The Connected Everything roundtable highlighted five opportunities to use digitisation to improve the manufacturing workforce of tomorrow (**Figure 4.7**).


**Figure 4.7**
Opportunities for the manufacturing workforce from digitisation

### Case Study 4: Unlocking Data-Driven Decision Making

**Project Partners:** Udacity

**Background**
The by-product of today's digital transformation is data. As the manufacturers emerges on the other side of that transformation, the ability to leverage the full potential of data science is quickly becoming a key factor in determining the long-term success of any business. This requires providing employees with the training and tools they need to address problems on the ground.

**Digital Manufacturing Application**
Udacity's Data Analytics and Machine Learning Nanodegree programs provided this a top manufacturer of aerospace technology with a simple, cost-effective way to train their workforce and close the skills gap—without hiring a single new employee.

**Outcomes**
Training the workforce to factor data-driven insights into their decision-making process helped unlock $13M year-over-year reduction in fuel costs and 10% reduction in airline delays.

### Data-driven decision making

Legacy manufacturing systems and approaches often fall short of optimal decision support, as data is not effectively captured and is often unused or underutilised. Modern manufacturing is becoming increasingly data-driven, due to the ever-increasing amounts of data generated by industrial internet of things devices and constant improvements in computing power required to process these vast volumes of data. Data generated through manufacturing activities are utilised to enhance manufacturing quality and thus enrich the flexibility and autonomy of the system. Data is used to develop data-driven models, that are powered by AI and machine learning algorithms, to make smart decisions. Data-driven, or autonomous, manufacturing systems, are capable of identifying solutions inconceivable to humans and thus open up new routes to improve productivity, resource efficiency and business gains.

## Improve transparency

Manufacturers are under increasing pressure to demonstrate their social and environmental sustainability. Digital technologies including AI, industrial internet of things and blockchain can be used for enhanced transparency of manufacturing processes and supply chains. Benefits from increased transparency include:

- **Greater collaboration and innovation:** By sharing data across companies, manufacturers can unlock additional value and accelerate innovation. The potential value of data sharing simply by focusing on manufacturing process optimisation has been estimated at over $100 billion, based on best practices [17].
- **Competitive advantage:** Consumers are increasingly considering Environmental, Social and Governance (ESG) factors when choosing between products or services. Furthermore, ESG factors are becoming more important to investors [67], so businesses that can clearly demonstrate their ESG credentials will benefit from a larger pool of capital, potentially at a lower cost, as well as, attract new customers.
- **Identify net zero manufacturing opportunities:** Using digital technologies to track emissions from materials and goods effectively, reliably and responsibly across the value chain could help improve processes, inventories and deliveries and reduce indirect emissions.

## Reduce digital skills barriers

Process engineering and factory operators working alongside industrial plants or manufacturing factories are some of the people best suited to identify areas for improvement, because they have tacit knowledge gained through years of experience of working on the manufacturing front line. However, they may not have the skills needed to create digital solutions themselves. Initiatives that encourage partnering between industry and academia enable manufacturers to access these skills (e.g. complex coding and modelling) and translate this into user-friendly bespoke solutions that can be used by non-specialists. However, if we are to encourage more widespread use of industrial digital technologies, they should be made simple, like setting up a new mobile phone app or using a self service checkout. An example of this is the low-code/no-code revolution that allows anyone to create software through more intuitive visual interfaces. This works to democratise the power to design flexible, scalable, customisable applications enabling manufacturing experts to design the digital solutions they need.

### Case Study 5: Training Field Technicians with Virtual Reality

**Project Partners:** Avangrid Renewables and Oculus (Meta)

**Background**
Field service professionals work in a range of different environments, supporting companies and customers with everything from intelligent devices to machinery. Avangrid Renewables is currently responsible for more than 60 wind power facilities spread across 22 states in America. In each of those facilities, professionals on the field must know how to effectively fix and maintain various wind turbines. As the Avangrid company has expanded, responding to the rising demands across the globe for clean energy, training managers have begun to struggle.

**Digital Manufacturing Application**
Virtual reality was used to curate elements from various types of technologies in-use by the company to create an all-encompassing experience. The training experience focuses on developing skills which keep employees operating as efficiently as possible in the field. Within the modules, users have access to a close simulation which demonstrates how each turbine runs.

**Outcomes**
Trainees now can practice their skills on the various turbines used by the brand as often as they want. Furthermore, they can learn how to troubleshoot the various turbine models in a way that doesn't require constant access to specialists and supervisors when on the move.

## New manufacturing roles

The employment impact of digitisation can have different dimensions. From an employment-level perspective, job loss related to automation when machines replace human input is widely discussed. At the same time, job creation is triggered by the emergence of new occupational profiles tailored to the exploitation of the new technologies. In its "Future of Jobs Report 2020," the World Economic Forum estimates that digitisation will displace 85 million jobs while creating 97 million new jobs across 26 countries by 2025 [68]. Early evidence for these predictions can be found in the European Company Survey (ECS) 2019, which shows a net increase in employee numbers since the introduction of digitisation (**Figure 4.8**).

To fill these future jobs, the workforce needs to understand how today's job roles and associated skills are morphing into new roles and career pathways that continue to evolve along with advanced technology. Deloitte Insights report, titled 'The future work of manufacturing", gives examples of a series of personas that describe what jobs could look like in 2025 (**Table 4.1**). By understanding the possible responsibilities and skills of future job roles, leaders, workers, educators and policymakers shape their vision and spark conversations around what needs to change to prepare the workforce to transition into these new roles.

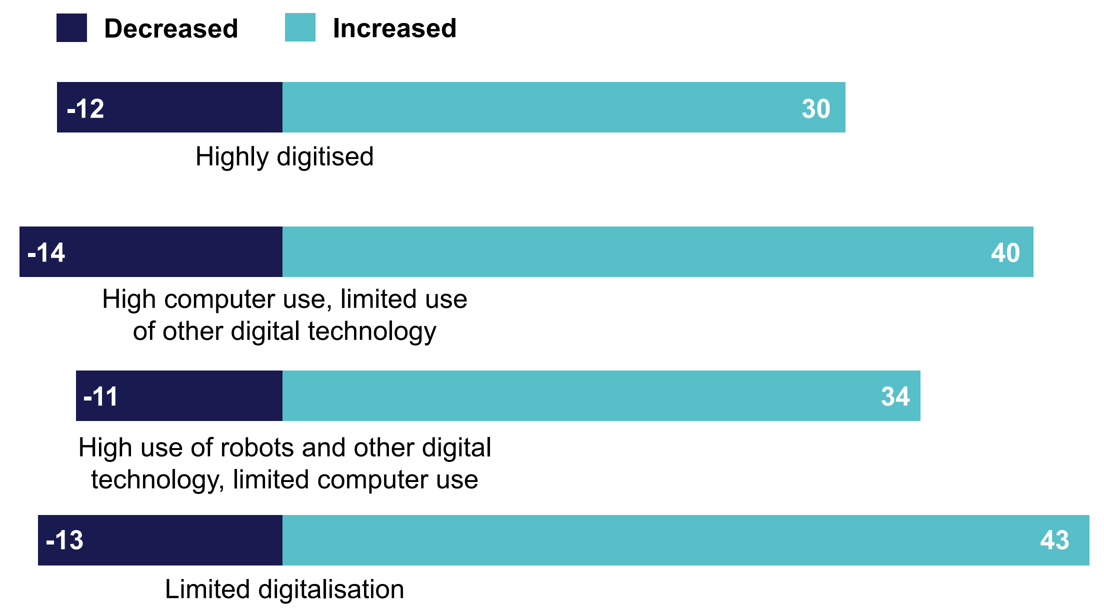



**Figure 4.8**
Change in number of employees since 2016 by digitisation intensity of establishments, EU27 and the UK, European Company Survey 2019 (%) [adapted from [69]]

## Wider business and social opportunities

Digitisation offers opportunities for businesses beyond manufacturing. Digital transformation provides a valuable opportunity for core business functions, such as finance and HR, to move away from manual processes and automate key areas like payroll, enabling leaders to focus on wider business opportunities.

### Case Study 6: Upskilling Workforce to Fit New Roles

**Project Partners:** Coca-Cola

**Background**
McKinsey Global Institute research estimates that one in every 16 workers will need to transition to new roles by 2030 (a 25 percent increase compared with pracademic predictions) to support increased demand for all things digital. Global consumer goods company Coca-Cola has established a digital academy to upskill managers and frontline team leaders across its business operations.

**Digital Manufacturing Application**
The digital academy is designed to build foundational knowledge and skills on core digital, analytics, and agile topics so that Coca-Cola associates can be successful operating in a digital world. The academy covers three major areas. The first area is around creating awareness and excitement. The second is around transformation skills, and the third is around digital and analytics skills.

**Outcomes**
Using go-and-see visits, boot camps, and e-learning modules, more than 500 people were given digital skills training in the first year. Graduates of the academy have implemented about 20 digital, automation, and analytics approaches at ten-plus sites in the company's manufacturing network, boosting productivity and throughput by more than 20 percent. Digital-skills training is now being rolled out to about 4,000 employees across the organisation.

| Role | Responsibilities | Skills |
|---|---|---|
| Digital twin engineer | • Create digital twins using 3D software and run simulations to measure product performance in varying conditions<br>• Draw insights from in-use product data to design new products and business models<br>• Use machine learning along with real-time usage and performance data to optimize product performance and service<br>• Work closely with the sales and marketing teams to create data-driven customer insights and go-to-market strategies | Simulations; analytics; sensors; software development; systems engineering; research and development; algorithms; image processing; team leadership; program management |
| Predictive supply network analyst | • Evaluates recommendations from the predictive system, such as scheduling and material orders and makes final decisions.<br>• Identifies market opportunities and proposes collaborative forecasts to customers based on analysis and insights from machine learning and artificial intelligence (AI) tools.<br>• Delivers results against key performance indicators, such as out-of-stocks, inventory cycle times and asset utilization, ensuring that customer service-level agreements have been met.<br>• Works collaboratively with engineering, production and logistics to calibrate demand and supply and eliminate any disruptions or delays. | ERP; demand analytics; inventory optimisation; network planning and optimisation; replenishment analytics; logistics and warehouse management; analytics; general digital fluency; visualisation |
| Robo teaming coordinator | • Observes robots and evaluates their performance based on how effectively they can perform predetermined tasks.<br>• Shares feedback with robot programmers on a robot's performance and recommends areas for improvement.<br>• Trains human team members to help them work more collaboratively with robots in a coworking environment.<br>• Works in tandem with robot coordinators from other departments to identify opportunities where robots can be deployed to enhance productivity.<br>• Delivers results against key performance indicators such as enhanced customer experience, human-hours saved and overall improvements in productivity. | Behavioural analysis; human-machine collaborator; robot management; administration; motion capture; social skills; customer service; technical training and orientation |
| Digital offering manager | • Works collaboratively with IT, UX designers and data science and finance teams to design and standardize digital offerings.<br>• Communicates and builds relationships with clients and external stakeholders.<br>• Translates customer needs, shares inputs and collaborates with the technical team to develop the offerings.<br>• Collaborates with data science experts to customize the offering, ensuring that service-level agreements have been met.<br>• Collaborates with UX designers to design the digital interface of the offering.<br>• Delivers results against KPIs such as enhanced customer experience, new offerings created, service score and client acquisitions. | Sales and marketing; behavioural analyst; customer experience; communication; network; collaboration; client management; social skills; change management; project management |

**Table 4.1**
Future manufacturing jobs roles and personas proposed by Deloitte Insights [70]



# 4.5. CONCLUSION AND RECOMMENDATIONS

The manufacturing workforce is currently facing a number of challenges including struggling to attract talent into the workforce, evolving career expectations and a widening skills gap.

Compounding this is the impact of digitisation on the workforce, which is expected to reshape manufacturing roles of the future and drive significant disruptions. When thinking ahead to 2050, manufacturers and educators must give existing workers the skills and knowledge needed to accommodate the new ways of working, while also training new workers to meet new challenges. Rising to this challenge will enable new opportunities from digital manufacturing for the future workforce. These opportunities include:

1. **Data-driven decision making:** Data-driven, or autonomous, manufacturing systems are capable of identifying solutions inconceivable to humans and thus open up new routes to improve productivity, resource efficiency and business gains.
2. **Improve transparency:** Digital technologies including AI, industrial internet of things and blockchain can be used for enhanced transparency of manufacturing processes and supply chains. Benefits from increased transparency include: greater collaboration and innovation, competitive advantage and the identification of net zero manufacturing opportunities.
3. **Reduce digital skills barriers:** Enterprises need to develop new digital solutions much faster than their competitors and automation software development tools such as low-code development platforms may be the response to these new companies' digital requirements.
4. **New manufacturing roles:** Digitisation will both displace and create new jobs within manufacturing. By understanding the possible responsibilities and skills of future job roles, leaders, workers, educators and policymakers can shape their vision and spark conversations around what needs to change to prepare the workforce to transition into these new roles.
5. **Wider business opportunities:** Digital transformation provides a valuable opportunity for core business functions, such as finance and HR, to move away from manual processes and automate key areas like payroll, enabling leaders to focus on wider business opportunities.



Opportunities from digital manufacturing require the leadership and the commitment of stakeholders from government, industry, education and professional organisations to ensure the future workforce has the required capabilities. From the Connected Everything roundtable discussion we make four recommendations to guide manufacturing workforce research agendas and policy, which are summarised in **Figure 4.9**.

**Promote continuous learning**
Continuous learning is the ongoing expansion of knowledge and skill sets. Often used in the context of professional development, continuous learning in the workplace is about developing new skills and knowledge, while also reinforcing what has been previously learned. To encourage employees to participate in continuous learning, it is important for organisations to create a supportive learning environment.

**Greater collaboration**
Greater support to connect manufacturing businesses with the UK innovation community, creating opportunities, increasing productivity and solving industry challenges. This will ensure future digital manufacturing research will develop solutions that fit manufacturing priorities.

**Support employee's wellbeing during transition**
Digitisation may lead to employee anxiety from the uncertainty of future job security and demand for reskilling. Communicating clearly and consistently with employees about how the opportunities digitisation offers them can help people engage with the digital transformation and not be left behind.

**Connect digital technology developers to manufacturers**
Greater support to connect manufacturing businesses with the UK innovation community, creating opportunities, increasing productivity and solving industry challenges. This will ensure future digital manufacturing research will develop solutions that fit manufacturing workforce priorities.

**Consolidate manufacturing skills guidance**
Workers and manufacturers seeking to understand what digital skills they need are exposed to many sources of, sometimes conflicting, advice about where to start. The current national standard for digital skills needs to expand beyond basic digital skills to include a skill development pipeline for future digital job roles.

**Figure 4.9**
Recommendations from Connected Everything roundtable discussion to support the development of the future UK manufacturing workforce

# 5. DIGITAL SUPPORT FOR ACHIEVING NET ZERO MANUFACTURING BY 2050

# 5.1. BACKGROUND

The concept of net zero greenhouse emissions has been gaining increasing attention from manufacturers, governments and society since it was first popularised by the Paris Agreement signed during the United Nations Climate Change Conference (COP21). The latest IPCC climate report makes it clear that in order to avoid the worst climate impacts, emissions need to half by 2030 and reach net zero by 2050 [71]. Recognising the need for urgency, over 80 countries have announced net zero targets and the Science-Based Targets initiative reports that over 2880 companies are taking meaningful action to reduce their emission [72].

The most recent emissions data published by Climate Watch (CAIT) exposes the manufacturing and construction sector to be the third largest sector in terms of carbon emissions [73], see Figure 5.1. In addition, a Global Supply Chain Report 2021 by CDP, found the impact of the indirect emissions from transport, sale, use and end life management of their products is 11.4 times higher than direction emissions [74]. This demonstrates the urgent need for the manufacturing sector to take positive steps in both reducing the emissions across the value chain and designing products that have a minimal environmental impact.

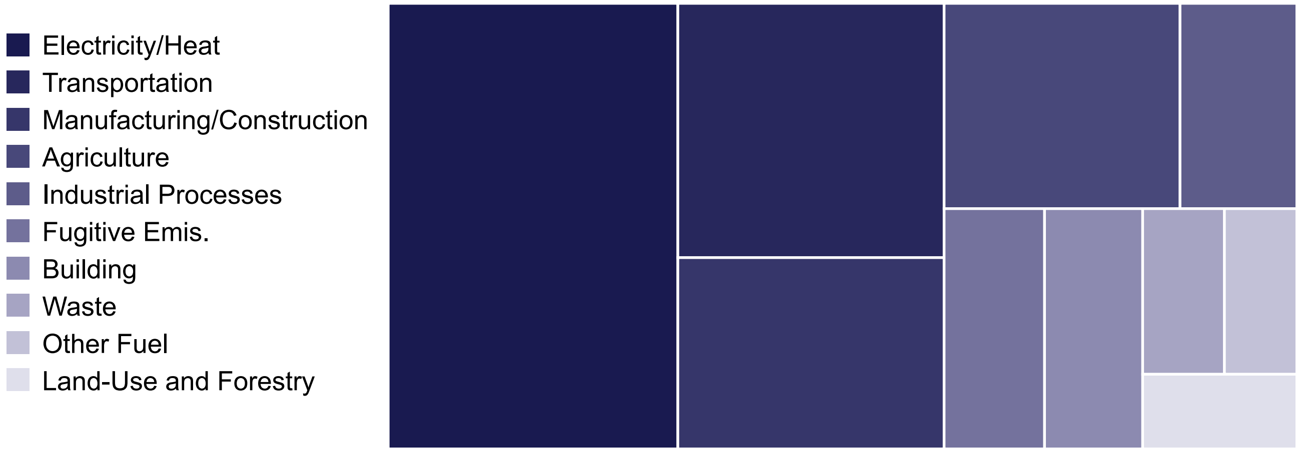



**Figure 5.1**
Breakdown of global carbon emissions across sectors. Data sourced from [73]

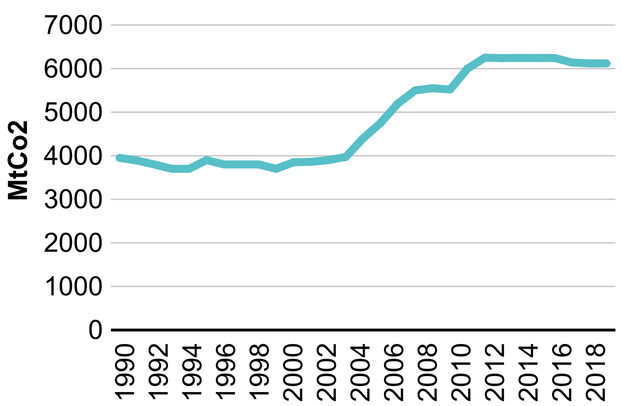



**Figure 5.2**
Historic global carbon emissions from the manufacturing sector. Data sourced from [73].

In the last two to three decades, there has been continued improvement in energy and process efficiency in manufacturing. However, **Figure 5.2** shows that up until 2010 emissions continued to increase, largely driven by the growing manufacturing sector in Asia [75]. Since 2010, direct manufacturing emissions appeared to have plateaued with only a small (4%) reduction since 2014. New disruptive technology and business models are required if the manufacturing sector is going to start reducing emissions and achieve net zero. Digital technology can play a role in helping achieve this goal by enabling a shift towards zero-carbon solutions. In the face of potentially catastrophic climate change, attention is increasingly turning to the potential of digital technologies as a tool for reducing and controlling emissions.



# 5.2. NET ZERO MANUFACTURING DRIVERS AND BARRIERS

## 5.2.1. WHAT'S DRIVING MANUFACTURING TOWARDS NET ZERO?

Understanding what is driving the shift towards net zero manufacturing is important if we are to develop transitional strategies that maximise these drivers and ensure manufacturers continue to invest in reaching net zero.

Three current net zero drivers and one future net zero driver emerged from the roundtable discussion (**Figure 5.3**)

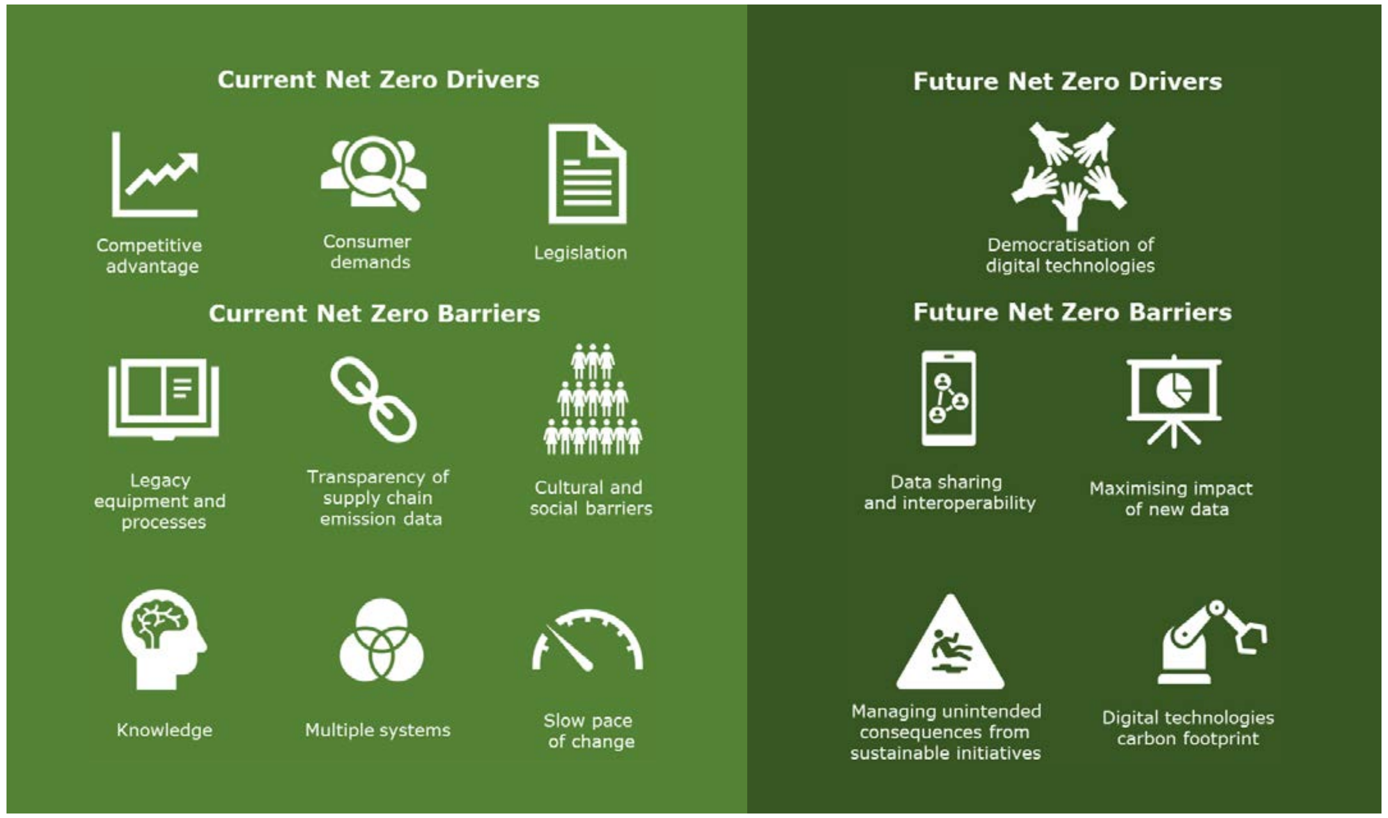



**Figure 5.3**
Net zero manufacturing drivers and barriers

## Competitive advantage

While the transition towards net zero will rely on an upfront investment by manufacturers, we predict that the competitive advantage from reducing emissions and improving overall sustainability will drive manufacturers towards achieving net zero manufacturing. The immediate economic benefits from reducing overall operational costs will be felt by reduced energy demand, improved efficiency, fewer travel costs and reduced waste. In 2022 onshore and offshore wind and solar power all now command about £40 per megawatt, gas fired power generation costs about £140 per megawatt hour [24]. Consequently, manufacturers that switch to renewable energy sources are likely to see lower costs per kWh than manufacturers who do not make the switch. Furthermore, environmental, social and governance factors are becoming more important to investors [67], so businesses with strong and clear commitments to net zero will benefit from a larger pool of capital, potentially at a lower cost.

There is a scarcity of the knowledge, abilities, values and attitudes needed to live in, develop and support a sustainable and resource-efficient society (i.e. green skills) within the manufacturing workforce. Manufacturers that lead the way by pre-emptively hiring employees with the skills necessary for a net zero transformation will have

an advantage over other manufacturers. Additionally, Pricewaterhouse Coopers (PwC) believe that in the future manufacturer's net zero credentials will make them more attractive to progressive-minded jobseekers and builds in-house expertise [76]. Finally, putting sustainability at the heart of their business strategy will open up opportunities for developing new products and entering new markets [77].

## Consumer demands

Manufacturers are experiencing pressure from a growing public demand for products that have a minimal environmental impact. When asked by the Institute of Engineering and Technology in 2020, the UK public believed that businesses have the second largest responsibility to address climate change, just below government's responsibility [78]. There is also an increasing number of people who not only want to support businesses with green credentials but are willing to pay a premium for sustainable goods and services. Overall, the split between willing and not willing to pay more for sustainable products is approximately equal [79]. However, 90% of people belonging to Gen Z are more willing to spend more on sustainable products, indicating that demand for sustainable products will continue to grow over the next few decades [79]. Equally important, 28% of consumers have stopped buying products due to ethical or environmental concerns [80].

## Legislation

Legislation is an effective tool for forcing companies to work within certain environmental limits. Previous legislation has targeted protecting natural habitats, keeping air and water clean, ensuring proper waste disposal, improving knowledge about toxic chemicals and helping businesses move toward a sustainable economy. Streamlined Energy and Carbon Reporting (SECR) was introduced in 2019, as legislation that requires obligated companies to report on their energy consumption and associated greenhouse gas emissions within their financial reporting for Companies House. Reporting on carbon emissions will provide consumers with the information needed to decide between brands from a sustainability perspective and ensure accountability from manufacturers. However, there is a significant number of Small and Medium Enterprises (SMEs) that make up the UK manufacturing sector (>135,000) who are excluded from this legislation due to the challenges associated with determining a product's carbon footprint. Given the large number of SMEs, they will play a crucial role in hitting the UK's net zero targets. Currently, this legislation only covers businesses that meet two or more of the following criteria:

- More than 250 employees
- Turnover in excess of £36 million
- Balance sheet in excess of £18 million

Future legislation will require businesses to also set long-term net zero targets and put plans in place to meet these targets. These must be science-based targets, meaning they are in line with the scale of reductions required to keep global temperature increase below 2°C above pre-industrial temperatures. By plotting the data available from the Science-Based Targets initiative, we can visualise the variability of net zero targets across manufacturing sub-sectors in terms of target years and emissions reductions (**Figure 5.4**). For example, the waste management sector needs a 37% reduction in emissions by 2030 to stay on target of limiting emissions by 1.5°C, whereas the automobile sector needs to achieve an almost 60% emissions reduction by mid-2030 to get to the stage where warming is well bellowed 2°C warming.



## The democratisation of digital technologies

Democratisation of technology refers to the process by which access to technology rapidly continues to become more accessible to more people. Leaps in technological innovation in areas like AI, cloud computing and robotics are powerful democratising factors in manufacturing, allowing companies to innovate faster, scale processes more quickly than ever before and reduce barriers like infrastructure or cost. Increased access to digital technologies will speed up the widespread manufacturing transition towards net zero manufacturing.

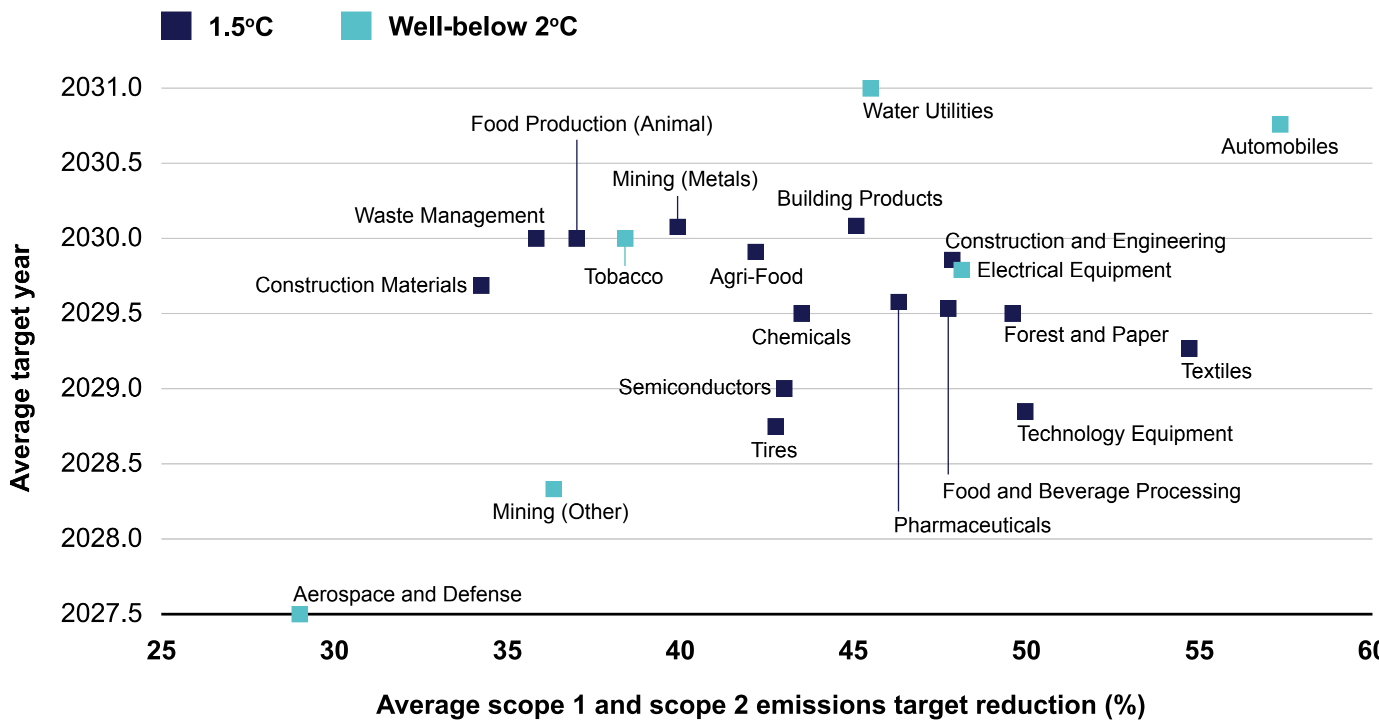



**Figure 5.4**
Average emissions reduction target and timeframe across businesses sectors. Data sourced from [72]

# 5.2.2. WHAT BARRIERS TO ACHIEVING NET ZERO MANUFACTURING WERE IDENTIFIED?

The Towards a Net Zero Carbon UK Manufacturing Sector 2020 report by Make UK [81], highlighted the biggest barriers to net zero manufacturing as perceived by manufacturers were:

- Insufficient return on investment
- Perception the required technology was too expensive
- Lack of knowledge or advice on what actions were needed

Interestingly, barriers relating to finance did not emerge from the Connected Everything roundtable, although, a lack of net zero knowledge was common among the barriers identified by Connected Everything and Make UK. In addition, four barriers were proposed that might emerge in the lead up to 2050 net zero manufacturing. Three out of the four of these barriers relate to preventing digital technologies from having the maximum impact to reduce emissions. Also of note was the fact that 2.5 times more barriers than drivers emerged from the roundtable discussion illustrating the scale of the net zero manufacturing challenge.

### Legacy equipment

Traditionally, manufacturing processes and equipment are designed to have at least a 20-year lifetime. As a result, most of the equipment on-site will have been in operation for several years or decades and are likely to have poor energy credentials. It is not always economically feasible, or environmentally friendly, to replace with newer less energy-consuming alternatives within the timeframe needed to meet net zero targets. This challenge is greater for manufacturing sectors with small profit margins (e.g. the food and drink industry), though, previous studies by the Advanced Manufacturing Research Centre demonstrate the feasibility of digitised legacy equipment for the goal of improving efficiency and reducing energy consumption which may help to, in part, address this barrier [82].

The intensive energy use by certain manufacturing sectors' legacy processes and equipment (e.g. steel industry) is a big challenge for achieving net zero manufacturing. Switching to renewable energy can help address emissions from energy-intensive sectors, though, producing renewable energy production at a scale sufficient to meet energy demands is not currently possible.

### Sharing emissions data throughout the value chain

In order to progress towards net zero manufacturing, manufacturers need to go beyond emissions-neutral operations within companies' boundaries and involve stakeholders from across their value chains and business ecosystems to tackle the largest contributors to the total emissions. Furthermore, the importance of establishing an emissions baseline is reinforced by the growing consciousness among society, and demand from consumers, investors and governments for the correct labelling of a product's emissions footprint.

Determining a product's emissions footprint helps benchmark decarbonisation efforts but is challenging due to a lack of data transparency. By sharing emissions data, manufacturers can obtain a complete and accurate value chain-wide emission footprint. This ultimately helps them identify the major contributors to the emissions footprint and reduce it. However, this is obstructed by the fact that (a) not all companies are required to measure and collect emission data and (b) the reluctance of manufacturers to share data across the value chain. Furthermore, exchanging data successfully requires overcoming both technical and trust-based barriers [17].

### Cultural and social barriers

A large number of organisations and countries have set net zero targets. However, this appears to vary between SMEs and large organisations, with larger employers having a much stronger focus on future environmental sustainability [78]. We need to recognise that organisations that are pressed for time and resources are unlikely to prioritise implementing net zero initiatives when employees have multiple other responsibilities. In addition, there is a danger that these targets trivialise net zero and serve only as lip service, particularly at the political level. For example, despite setting net zero targets, a House of Lords 2022 report by the Industry and Regulators Committee noted that the government is not currently on track to achieve their net zero targets [83].

On a global basis, household consumption accounts for almost three-quarters of greenhouse gas emissions [84]. Research has shown that society needs to break with previous mindsets to make small and easy changes. Instead, high impact shifts in consumer behaviours and choices are needed that are consistent with the scale of the climate challenge, build optimism and commitment and give weight to new ambitious narratives that inspire wide public participation [84].

### Knowledge

There is no one pathway to net zero manufacturing, it is unknown and risks causing manufacturers reputational damage if executed poorly. Manufacturers report a lack of knowledge about low carbon alternatives, lack of benchmark quality insights and data, lack of information about low carbon alternatives. When asked by The Institution of Engineering and Technology in 2020, 88% of manufacturers say their business needs new skills and knowledge to deliver their sustainability strategy [78].

### Multiple systems

Manufacturing systems are made up of multiple interdisciplinary, often international, stakeholders with different priorities, agendas and regulatory frameworks. As previously mentioned, manufacturers need to go beyond emissions-neutral operations within their system boundaries and involve stakeholders from across their value chains and manufacturing ecosystems to tackle the largest contributors to total emissions. This is complicated when stakeholders have other, sometimes conflicting, sustainability goals (e.g. decrease in resource consumption, circular economy). Moreover, the logistical complexity of getting multiple stakeholders across the value chain to work together to reduce emissions hinders the implementation of extensive net zero manufacturing strategies.

### Slow pace of change

The slow pace of digital transformation within manufacturing demonstrates the challenges associated with introducing transformative technologies and business models. Reforming manufacturing requires synchronised and focused action from various stakeholders such as managers, policymakers and members in the supply chain, which takes time to coordinate. New technologies are rarely implanted into manufacturing processes straight away but undergo time-consuming pilot trials and evaluations. However, in the face of potentially catastrophic climate change, manufacturers are required to evolve faster than ever before to decarbonise their processes and products. **Figure 5.4** illustrates that the scale and rate of change required is not equal across manufacturing subsectors.

### Data sharing and interoperability

Data sharing across the value chain is a key enabler of many digital technology solutions, including using digital technology to improve sustainability. As previously alluded to, there are technical and trust-based barriers inhibiting data sharing. Interoperability is the ability of computer systems or software to exchange and make use of information. Research is required to ascertain how we solve high level data fusion and data interoperability, and information standards challenges to create connected, sustainable infrastructures. This will ensure that we can respond in real time to enable industry to become data-driven in terms of sustainable decision making.

### Maximising impact from new data

Digital manufacturing is increasing the volume and variety of manufacturing data available. There has been a tendency to push for the collection of more and more data, with the assumption that more data will lead to greater insights, though, the environmental impact of collecting and storing high volumes of data has been gaining attention. High data volume requires extensive facilities for storage using natural resources such as water and non-renewable energy. Therefore, we need to understand what data is of actual value to collect with the aim of improving manufacturing productivity and sustainability. Additionally, understanding how to create value from data can become overwhelming as data volume and variety increases. Researchers also need to provide guidance on how high volume data can be best utilised to reduce the environmental impact and set up frameworks to support the whole data-driven modelling pipeline, from collection, processing and modelling of data to translating the data insights/recommendations into the manufacturing business.

### Unintended consequences from sustainable initiatives

As manufacturers seek to take positive steps to reduce their emissions, it is important to understand the risks involved in making that transition. This is not to inhibit positive change, but to focus on the risk implications and ensure that measures are taken to ensure a safe and sustainable future. Decisions made now to upgrade or change production processes have an impact for years to come due to the 20 years+ lifetime of machinery equipment and processes. Therefore, careful consideration is needed in the design phase so that manufacturing processes will remain environmentally sustainable for years to come and consider future environmental challenges. The Centre for Sustainability and Excellence recommends answering the following questions to help identify the sustainability considerations [85]:

- Which stakeholders will be impacted? Employees, local community, investors?
- What is the time horizon? Sustainability is a long-term and often incremental endeavour.
- What does the life cycle analysis reveal? Responsibility neither starts nor ends with the purchase of the tech.
- Where does the tech fit in the circular economy?
- Is the technology, and subsequent touting of, greenwashing?
- What might be the unintended consequences? Displaced workers, data breaches?

### Environmental impact from digital technologies

Digital transformation has the potential to improve efficiency and productivity across all sectors, and help to dramatically reduce carbon emissions in agriculture, transport, planning, building, waste management and public services. However, the use of digital technology comes with its own energy cost, and as the world becomes increasingly reliant upon the internet and connected devices, it is important to acknowledge and manage the environmental impact. Data centres alone are predicted to produce 1.9 gigatonnes, or 3.2% of the global total, of carbon emissions by 2025 [35] as a rapidly increasing number and variety of IoT electronic devices in a wide range of end-use sectors require massive data communication in terms of volume, velocity/speed, and variety. Semiconductor technology advancements have played a key role in ICT and unlike the past ICT energy footprint analysis, which focused on the final electronic product, an attempt has been made to examine the global energy impacts for the period 2016–2025 based on the market forecasts of three major IoT IC types, i.e., sensors and actuators, connectivity, and processor ICs distributed among four major IoT device components. Total global IoT semiconductor primary energy demand is projected to increase from 2 EJ in 2016 to 35 EJ by 2025, resulting mainly from a substantial projected increase energy needed in the manufacturing of ICs, with growth in the use of sensors and energy-intensive next fab generation manufacturing. Unlike the trend in manufacturing energy, total global operational energy use is projected to decrease significantly with the development of smaller transistor size, low-power devices, and faster wireless data communication technology. Total operational energy is projected to significantly decrease from 118 TWh/year (1,2 EJ/year. Furthermore, a diverse range of metals are needed to make digital technologies. Critical Raw Materials (CRM) are a list of finite materials released by the European Commission that are in scarce global supply. Limited or decreasing access to CRM is cause for world-wide concern due to their links to technology, industry needs and the environment. In 2021 the UK government published their own list of critical materials, identify 18 materials of high risk in terms of their global supply risk and the UK economic vulnerability to such a disruption [86]. For example, server, storage and networking equipment contain 23 out of 30 CRMs [87]. While electronic waste recycling offers some hope, due to the mass of CRM in electronics being smaller in comparison to other materials that feature within IT equipment, it's common that the CRMs are destroyed and sent to landfill as a result of the 'recycling' process.



# 5.3. HOW CAN DIGITAL TECHNOLOGIES SUPPORT NET ZERO MANUFACTURING?

Existing industrial digital technologies (e.g. the Industrial Internet of Things, machine learning, sensors) have the potential to deliver nearly one-third of the carbon emission reductions required by 2030 [39]. Digital manufacturing enables many routes towards net zero manufacturing. For example, digital technologies can give manufacturers a better understanding of their energy usage and make intelligent recommendations to increase efficiencies. Additional examples include robotic automation that optimises energy and materials consumption and digital twins identifying ways to remove waste from key processes. From the roundtable discussion, five ways by which digitisation can help manufacturers reduce their emissions emerged (**Figure 5.5**).


**Figure 5.5**
Uses of digital technologies to support next zero manufacturing that emerged from the roundtable discussion.

## Digital enabled circular economy

The circular economy is vital to achieving a net zero manufacturing vision, due to the significant potential it holds for climate mitigation and resilience through rethinking and redesigning our socio-economic system, regenerating the natural world, reducing the need for virgin materials and reusing and recovering resources to avoid waste [88]. *"Currently, most of what we consume flows through a linear, 'take, make, waste' economy, in which products and materials are made, used, and then thrown away. A Circular Economy, by contrast, focuses on regeneration, restoration, and re-use at all stages of a resource's life cycle. This allows products, materials, and components to remain in circulation at their highest value for the longest period, and the waste generated by a linear economy is designed out from the start* [89]."

A challenge for manufacturers is that materials are not infinitely reusable or recyclable. Manufacturers need information on the materials or products they recover so they can restore the highest possible value for as long as possible. For example, plastic recyclers are not always aware of the full chemical makeup of the materials they process, including the presence of toxic substances. Additionally, repair technicians don't always have access to disassembly guidelines for electrical equipment. To maintain the value of a product in the economy for as long as possible, information on the product design, composition and the condition is critical. Therefore, for manufacturers to embrace a circular economy the equation is no longer "waste = resource" but "**waste + information = resource**" [90].

Digital technologies enable materials and products to have a digital footprint, so data about a product or material use can be captured, stored shared and analysed throughout its lifecycle. The technologies to achieve this are referred to as either attached or embedded anchors and they can be physical (e.g. fluorescent markers, or watermarks), digital (e.g. radio frequency identification or printed electronics) or biological (e.g. chemical tracers or DNA markers) [91].

### Case Study 7: AI Waste Analytics

**Project Partners:** Greyparrot

**Background**
Despite consumers' best efforts to recycle, poor packaging design and ineffective sorting means that much of what goes into recycling bins still ends up in landfill. Manual spot sampling is limited by time and resource constraints and as a result, covers a very small proportion of all processed waste.

**Digital Manufacturing Application**
Greyparrot is an AI start-up using computer vision technology to monitor, analyse and sort tonnes of waste at scale. The robust AI monitoring unit analyses 100% of waste, providing users with live composition data at scale. The integrated AI model recognises the composition of objects automatically and in real time. The system is designed to be retrofitted without changing existing infrastructure.

**Outcomes**
Since its inception in 2019, the Greyparrot AI-powered computer vision system has analysed over ten billion packaging items in sorting plants to increase recycling rates and introduce accountability to the waste value chain. Its customers cover 60% of the waste management market including industry leaders such as Suez, Biffa and Veolia. The unprecedented data the company has gathered on product packaging is directly impacting policy and packaging design, enabling data-backed decisions to be made by stakeholders along the entire waste value chain.

## Green digital energy systems

The energy consumption within manufacturing processes is the largest source of carbon emissions [73]. The European Commission outlines how energy system integration – the coordinated planning and operation of the energy system 'as a whole', across multiple energy carriers, infrastructures and consumption sectors – is the pathway towards an effective, affordable and deep decarbonisation of the economy [92]. Digital technologies will be key to making energy systems more connected, intelligent, efficient, reliable and sustainable over the coming decades. Furthermore, digital transformation is crucial in the renewable energy transition, allowing the integration of more renewable energies throughout the electrical system, increasing network reliability and helping to better manage energy demand.

Digitisation supports energy system integration by enabling dynamic and interlinked flows of energy carriers, allowing for more diverse markets to be connected with one another and providing the necessary data to match supply and demand at a more disaggregated level and close to real time. A combination of novel sensors, advanced data exchange infrastructures and data handling capabilities that make use of Big Data, Artificial Intelligence, 5G and distributed ledger technologies can enhance forecasting, allow the remote monitoring and management of distributed generation and improve asset optimisation, including the on-site use of self-generation. Digitisation is also key to unleashing the full potential of customers having flexible energy consumption across different sectors to contribute to the efficient integration of more renewables.

### Case Study 8: Intelligent Tidal Turbine Control Systems

**Project Partners:** ELEMENT

**Background**
The future of commercial tidal energy rests on today's efforts to reduce operational overheads and maximise energy outputs from arrays. Sensors have historically presented a significant cost to tidal energy producers as they require replacing and repairing when affected by biofouling, corrosion and other common effects of the marine environment.

**Digital Manufacturing Application**
The ELEMENT team will used modelling to create the world's first intelligent tidal energy turbine, using its rotor and drivetrain as a sensor. This transformation eliminates the need for separate sensors to be attached to the turbine.

**Outcomes**
This move reduced operating costs by delivering greater operational control over the turbines, improving their reliability, lessening exposure to damaging loads and extending the lifetime of components. Other benefits are better control over environmental impacts and finer adjustment of turbines to tidal flows so they can maximise energy capture. In total, ELEMENT delivered a 17% cost saving on the levelised cost of tidal energy thanks to reduced operating costs combined with maximised lifetime, energy capture and availability.

## Track value chain emissions

Switching to clean energy and using digital technologies to improve manufacturing efficiencies can help reduce direct emissions but decarbonising indirect emissions from the industry remains a significant challenge. Measuring the life-cycle emissions of products is the most meaningful way to illustrate how raw materials' production, manufacturing processes and use affect an overall carbon footprint. However, value chain emissions are notoriously difficult to measure. Using digital technologies to track emissions from materials and goods effectively, reliably and responsibly across the value chain could help improve processes, inventories and deliveries and reduce indirect emissions. In addition, tracking and sharing emission data across the value chain will enforce greater transparency and accountability. Benchmarking emissions data information across manufacturing may yield a faster reduction in emissions and control sustainable manufacturing and material costs, as it will ensure environmental, social and governance compliance and will help build consumer loyalty for brands with sustainability appeal.

Measuring value chain emissions requires a high level of integration and coordination between multiple supply chain networks. Furthermore, mechanisms to increase trust in the data collected are required. Digital technologies including AI, Industrial Internet of Things and blockchain can be used for enhanced transparency, as well as to make it easier to track carbon emissions. Capgemini reports that by reporting carbon emissions across a blockchain network, a single platform for carbon measurement is created, helping to provide a trusted network that can report emissions in an immutable and tamper-proof audit trail, facilitating connections between all the different participants around a trusted platform that guarantees privacy, security and traceability [93]. Businesses can use technologies to understand the carbon footprint of products and services across whole value chains. Insights gained can be used to make the right design decisions for in-built net zero. In addition, mapping, tracking and visualising energy data will improve energy management and reduce usage. In the future, apps will integrate multiple sources of data and provide intuitive dashboards and visual tools for consumers to track their emissions and gain insight into the impact of their food choices, shopping and travel habits [39].

## Data-driven sustainability

Data-driven sustainability refers to collecting and using data to make decisions that guide measurable and environmental and socially responsible manufacturing strategies. Whether these strategies are aimed at lowering greenhouse-gas emissions, optimising supply chains, or reducing waste, insights from data can power positive change while increasing productivity. Digital systems from ground sensors to satellites can generate valuable data to support data-driven decision-making, by enabling greater emissions monitoring and understanding of climate trends and intervention impacts. According to Drax, 85% of key decision-makers in manufacturing see data analysis as a top priority for achieving net-zero. Data can be used to develop data-driven models, that are powered by AI and machine learning algorithms, to make intelligent sustainable decisions governed by the data. Data-driven, or autonomous, manufacturing systems are capable of identifying solutions inconceivable to humans and thus open up new routes to improve productivity and resource efficiency and reduce emissions. For example, research published by The Royal Society outlines how the opportunity to bring together governments, academia, industry and the third sector could lead to the creation of a 'planetary digital twin' or operational 'control loop for the protection of the planet' [94]. The digital twin could then be used to simulate, optimise and transform economic activity to minimise emissions and maximise efficiency. Similarly digital twins built describing manufacturing systems would also allow manufacturers to explore 'what-if' scenarios and impacts of interventions to reduce emissions.

The effectiveness of utilising data to improve manufacturing is dependent on the quality of the data collected. The data collected must be appropriate to the situation; therefore, calculated decisions must be taken to identify how the data is collected and the required granularity of that data. Furthermore, the environmental benefit from the insights gained from the data must outweigh the environmental impact of collecting and storing the data.

### Digital support to design new generation of sustainable products

According to the Circular Economy Action Plan 2020, "up to 80% of products' environmental impacts are determined at the design phase". We are currently living in a world where more and more data is captured throughout a product's life cycle (from design to product retirement). The networks are evolving, wherein, data are collected from all phases of the product lifecycles from design, prototype, manufacturing, usage aftermarket, returns remanufacturing and recycling. Integrating product use and customer data into the design process is regarded as essential in the next generation of sustainable products for manufacturers to remain competitive. New approaches to intelligent design automation, such as generative design, have the potential to accelerate the iteration of more innovative products that perform better and last longer. Digital manufacturing presents a view of product and process design holistically, as part of the product life cycle, and allows products to be designed in a way that adjusts for process capabilities or limitations. Furthermore, material used, assembly and transportation can be optimised thereby reducing the amount of waste and energy used during manufacturing.

### Case Study 9: Self-Optimising Clean-in-Place

**Project Partners:** University of Nottingham and Whitwell

**Background**
The 30% of energy and water used by the UK food and drink manufacturing sector is used to clean processing equipment. Today's Clean-in-Place (CIP) systems do have some drawbacks. CIP processes need to be designed for the worst case scenario, and they operate 'blind'. They are unable to identify how much food or microbial debris remains within the equipment which means that cleaning takes place over a set time period, rather than bearing a relation to the amount of cleaning that is actually required. The financial losses incurred by this lost production time are exacerbated by the over-use of energy, water and chemicals due to over-cleaning.

**Digital Manufacturing Application**
The self-optimising clean-in-place (SOCIP) system uses an artificially intelligent, multi-sensor inspection system to monitor and assess exactly how much food residue and microbial debris is left inside the manufacturing equipment during the pre-rinse and detergent phases of the cleaning process. SOCIP's intelligent software assesses the cleaning process and optimise the length of time required for each CIP phase – maintaining hygiene standards and improving efficiency, as the equipment is cleaned only for as long as necessary.

**Outcomes**
A medium-sized UK diary will, typically spend £1 million a year on cleaning, with lost production time accounting for at least half of this cost. Reducing CIP time to just what is required to ensure the equipment is clean would enable the dairy to reduce its annual water and energy use by around 270,000l and 2,400Mwh respectively, resulting in net savings of around £300,000 a year.



# 5.4. CONCLUSION AND RECOMMENDATIONS

The digital transformation of manufacturing offers a way forward towards net zero manufacturing by 2050.

The scale of the net zero challenge demands new technologies and models for innovation be explored, to overcome the numerous barriers from decarbonising legacy equipment and processes to integrating net zero solutions that span multiple manufacturing systems. Government, funders, industry and academia from computer science to social sciences must combine research and development efforts to greater effect to overcome these and future net zero barriers. This study highlights five methods of using digital technologies for manufacturers to continue towards net zero.

1. **Digital enabled circular economy:** Digital technologies enable materials and products to have a digital footprint, so data on product design, composition and the condition is captured. This information can be utilised to extend a product's life, as well as identify new reuses opportunities and/or paths to recovery material through valorisation processes.
2. **Green digital energy systems:** Digital transformation is crucial in the renewable energy transition, allowing the integration of more renewable energy throughout the electrical system, increasing network reliability and helping to better manage energy demand.
3. **Track value chain emissions:** Digital technologies concepts, such as AI, Industrial Internet of Things and blockchain can be used for enhanced transparency, as well as making it easier to track carbon emissions. Insights gained can be used to make the right design decisions for in-built net zero.
4. **Data-driven sustainability:** Data can be used to develop data-driven models, that are powered by AI and machine learning algorithms, to make intelligent sustainable decisions governed by the data.
5. **Digital support to design new generation of sustainable products:** Digital manufacturing presents a view of product and process design holistically, as part of the product life cycle, and allows products to be designed in a way that adjusts for process capabilities or limitations.
6. Maximising digital technology's contribution to the net zero 2050 target will depend on the policy decisions we make today, and the actions of governments, industry and funders. From the Connected Everything roundtable discussion we make 12 recommendations to guide net zero manufacturing future research agendas and policy, which are summarised in **Figure 5.6**.

### Legislate for net zero manufacturing
Current legalisation does not give sufficient impetus to manufacturers to decarbonise. Tougher legislation is needed to encourage manufacturers to reduce emissions and support the development of environmentally friendly manufacturing techniques and processes.

### Adaptive regulation to keep pace with innovation
Net zero solutions will exploit several levels of technology integration and highly collaborative product and process development. Fast pace, adaptive regulation is required for this to be effective.

### Integrate net zero within environmental policy
Emission reduction policies need to look beyond carbon to ensure their wider environmental contribution is a positive one.

### Financial support to decarbonise manufacturing
Additional funding and an adapted fiscal and financial landscape to incentivise low carbon but higher cost processes and products.

### Consolidate net zero manufacturing guidance
Manufacturers seeking to decarbonise are exposed to many sources of, sometimes conflicting, advice about where to start. A national platform is required that consolidates the net zero manufacturing guidance and expertise.

### Enable a shift towards a sustainable society
Social and behavioural changes are paramount to achieving net zero and this will require multiple inventions (*e.g. education campaigns, product carbon footprint labelling, price increases*) to achieve.

### Support employee's wellbeing during transition
Implementing net zero technologies and processes can cause employee anxiety. Communicating clearly and consistently with employees about how the company is tackling net zero can help people feel part of the solution and not the problem.

### Greater collaboration
Greater collaboration between manufacturers and researchers is needed to both ensure research is meaningful and to translate net zero research into industry.

### Transparency of value chain emission data
To enable net zero manufacturing, support to improve data sharing and transparency is needed to understand the environmental and social impact of manufacturing decisions, to drive more sustainable choices.

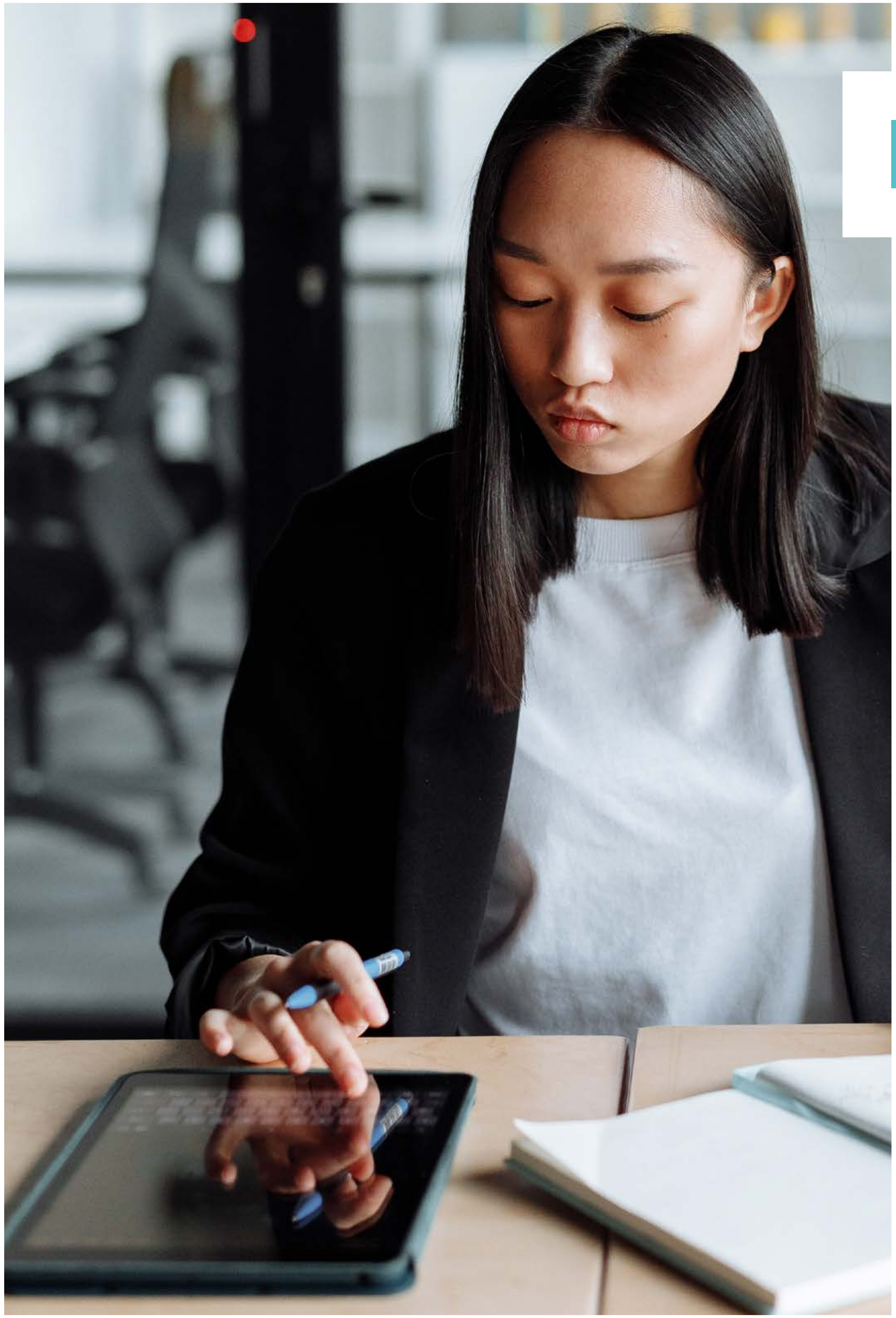
### Guidance for wider systems thinking
Manufacturers need guidance to understand emissions across the wider system (scope 3 emissions) so they can identify significant contributors and take steps to reduce these emissions.

### Support design of sustainable products
The product design stage is crucial to minimise a product's emission during manufacturer, use and end life. Support is required to filter down product sustainability data and decision-making tools to designers.

### Understanding digital technologies' impact
Digital technologies have their own carbon impact which must be understood to ensure their introduction leads to an overall emissions reduction. In addition, manufacturers must be wary of using digital technologies to fix unsustainable practices.

**Figure 5.6**
Recommendations from roundtable discussion to support manufacturers achieve net zero manufacturing





# 6. DIGITALLY ENABLED MANUFACTURING RESILIENCE

# 6.1. BACKGROUND

Over the past two years, manufacturers have faced unprecedented disruption with the combination of the UK leaving the European Union, the global pandemic and the humanitarian disaster in Ukraine, combined with soaring transport, energy and raw material costs.

Digital Catapult research reveals that two-thirds of manufacturers are prioritising building resilience into their supply chains during 2022 and this is driving their innovation goals [95]. The manufacturing sector is, directly and indirectly, responsible for over 7 million UK jobs and increasing its resilience is vital to ensure national economic and social sustainability. The value of a resilient manufacturing sector was underlined during the UK's response to the pandemic. Whether by scaling up the production of critical supplies for the healthcare sector or maintaining food production, manufacturing firms have shown their importance in a time of national crisis. Furthermore, opportunities from transforming manufacturing resilience in the UK could add £26bn of productivity value to the economy [96].

A system is resilient if it can adjust its functioning prior to, during, or following events, and thereby sustain required operations under both expected and unexpected conditions. For a system to be resilient against disruptive events there are two essential properties that a system should possess. The first is the ability of the system to maintain function without failures, generally referred to as "reliability." The second is the ability of the system to recover from misfortunes, a.k.a "recovery" or "recoverability". Digitisation can play a key role in making manufacturing systems more resilient through speeding up recovery from disruptions (i.e., resuming operations), diversification (i.e., exploring new feedstocks, products and new markets) and increasing reliability (i.e., preparing for supply/demand shocks and operational risks).

Therefore, this theme aims to:

- Identify the resilient manufacturing drivers and barriers.
- Understand how digitisation may enhance resilience within manufacturing.
- Recognise what risks digitisation poses to manufacturing.
- Provide recommendations to ensure the future UK manufacturing sector is resilient.



# 6.2. RESILIENT MANUFACTURING DRIVERS AND BARRIERS

## 6.2.1. WHAT'S DRIVING MANUFACTURING TO INCREASE RESILIENCE?

The recent distributions caused to the global supply lines are currently driving manufacturers' interest in becoming more resilient. Yet, history tells us that companies often lose interest in resilience as crises fade.

Therefore, by understanding what additional drivers exist will help communicate the importance of resilient manufacturing when the recent disruptions are resolved and ensure manufacturers continue to invest in resilience. During the Connected Everything roundtable discussion, four current resilient drivers and three future net drivers were identified by the delegates (**Figure 6.1**).

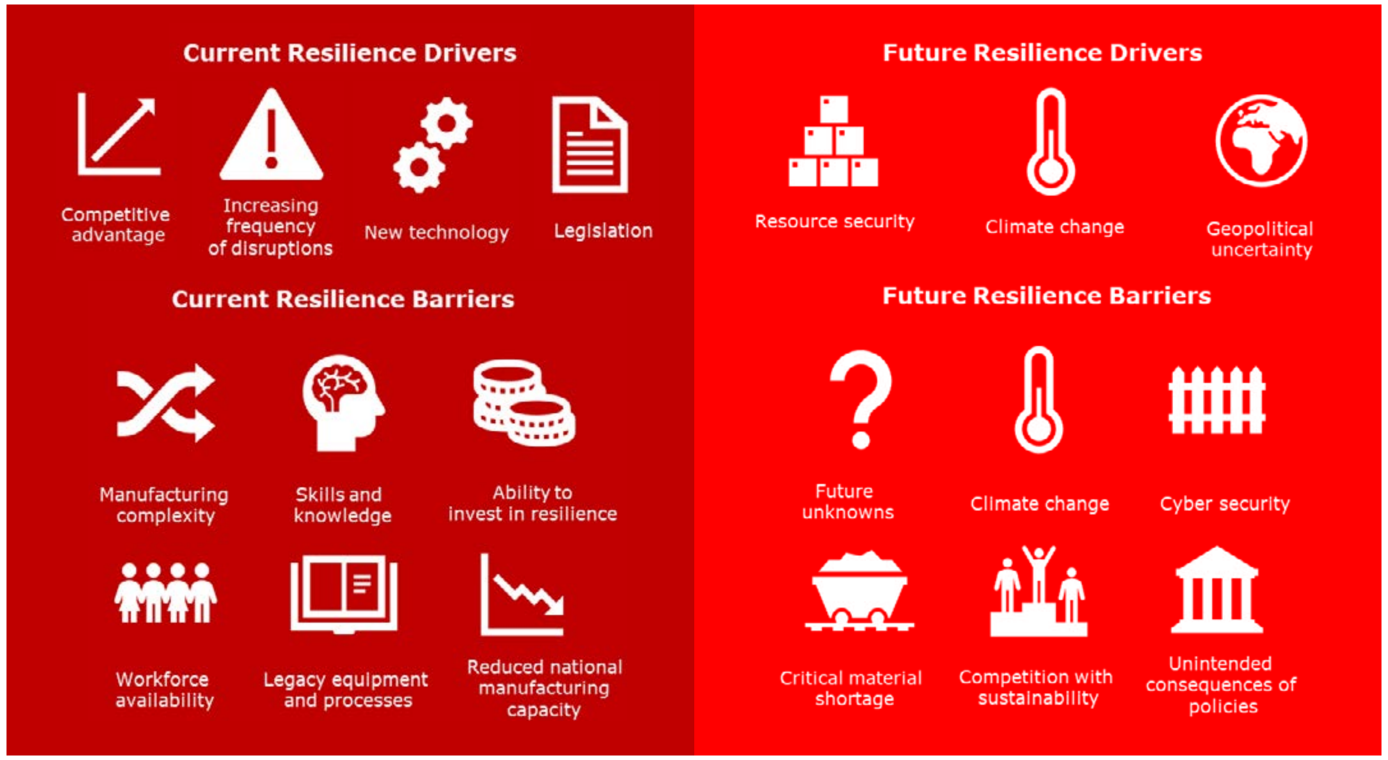



**Figure 6.1**
Resilient manufacturing drivers and barriers

## Competitive advantage

Resilience has not always been a priority for manufacturers, with many today believing it to be only valuable in a limited and non-recurring set of circumstances. However, resilience during crises can instead offer opportunities for differential growth and competitive advantage. For example, research from The BCG Henderson Institute shows that 30% of a company's long-run relative total shareholder return is driven by how it performs during crises [97]. Resilient manufacturers enjoy better outcomes than their competitors through a combination of three components of performance (**Figure 6.2**):

- **Lower shock impact:** Resilient manufacturers limit the immediate impact of the shock due to recognising threats and preparing for them in advance and their ability to mitigate or absorb the immediate negative effects of a shock.
- **Faster recovery speed:** Resilient manufacturers recover faster than the competition due to their preparedness to capitalise on disruption during a crisis and their ability to quickly identify the actions needed to restore operations and implement them swiftly.
- **Greater recovery extent:** Resilient manufacturers thrive in the new circumstances after a crisis, due to their adapting to the new normal post-shock and their shaping of the dynamics of the industry in the post-shock environment to their advantage.

## Increasing frequency of disruptions

Disruptions across the value chain show little sign of abating. In fact, future pandemics, global events, resource uncertainty, workforce depletion and climate change mean manufacturing systems will be subject to a greater frequency of unforeseen disruptions. For example, research by McKinsey Global Institute illustrates how the probability of a hurricane of sufficient intensity to disrupt semiconductor supply chains may grow two to four times by 2040 [98]. As the frequency and magnitude of the disruptions increases, applying ad hoc measures to restore steady-state operation will become increasingly expensive and difficult. Furthermore, the effect of these disruptions may be linger long after the initial cause. For example, more than two years after the pandemic began the gap between semiconductor supply and demand has widened across all semiconductor-enabled products.

## New technology

As the digitisation of the manufacturing sector becomes increasingly prevalent, this, in turn, will drive resilience improvements. More than three-thirds of leaders surveyed by Deloitte said their organisation's digital capabilities significantly helped them cope with challenges caused by the pandemic [99]. Indeed, during the pandemic, many manufacturers accelerated their digital transformation to better deal with and adapt to the disruptions caused [14]. Industrial digital technologies, such as machine learning and the internet of things, will enable a data-driven approach that will give manufacturers better awareness to take action on or compensate for unanticipated problems. For example, digital products have been developed at Value Chain to solve scheduling inefficiencies by enabling better foresight of customer demand that in turn can facilitate intelligent decision making with regarding to scheduling jobs [100]. Furthermore, as we progress towards 2050 innovation will go beyond current digital solutions (e.g. extended reality, telepresence, virtual production and simulation) and offer new opportunities to increase resilience.

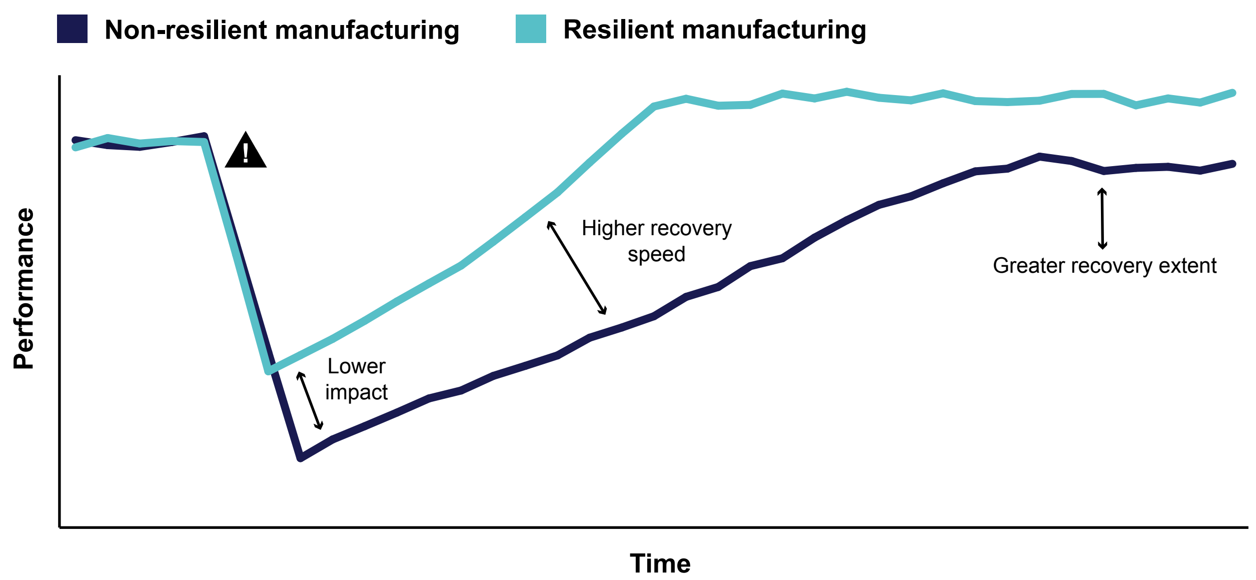



**Figure 6.2**
Three components of competitive advantages derived from resilience. Figure adapted from [97]

## Legislation

As a general rule, governments will point manufacturers towards and recommend relevant standards but stop short of mandating their uptake. However, recent legislation is playing a role in driving manufacturers to become more resilient. For example, water utility companies within the UK must meet customer satisfaction benchmarks for continuous service as criteria to get new investments approved [101]. That has encouraged United Utilities and Severn Trent, among others, to invest in machine learning analytics and IoT to spot mechanical breakdowns, sewage overflows and other unexpected disruptions [102,103]. In the future, as part of the £2.6 billion National Cyber Strategy 2022, the UK Government is working to improve the cyber resilience of businesses and organisations across the UK economy [104].

## Future resource security

The products made by manufacturers consume a large number of resources (e.g. water, metals, minerals and natural materials). Since 2011, the EU has identified those raw materials that are most economically important and have a high supply risk and now refer to them as critical raw materials [105]. Critical raw materials are essential to the functioning and integrity of a wide range of industrial ecosystems. Tungsten makes phones vibrate. In 2021 the UK government published their own list of critical materials, identify 18 materials of high risk in terms of their global supply risk and the UK economic vulnerability to such a disruption [86]. Gallium and indium are part of light-emitting diode (LED) technology in lamps. Semiconductors need silicon metal. Hydrogen fuel cells and electrolysers need platinum group metals. It is projected that it will take until 2100 before recycling and valorisation can account for at least half of the number of rare earth elements that the world will need [106]. Therefore, achieving resource security requires action to diversify supply from both primary and secondary sources, reduce dependencies and improve resource efficiency and circularity, including sustainable product design.

## Adapting to climate change

Despite progressive action on climate change by both governments and companies, temperatures will still result in 2.7°C of warming by 2100, according to the UN Intergovernmental Panel on Climate Change, which exceeds the 1.5°C threshold needed to avoid climate change impacts [107]. As climate change makes extreme weather more frequent and/or severe, it increases the probability of events that are more intense than manufacturing systems are constructed to withstand. Therefore, it may be necessary for manufacturers to increase investment in adaptation, possibly at the expense of productivity. The United Nation adaptation development plans may include: how to manage the increasingly extreme disasters we are seeing; how to protect coastlines and deal with sea-level rise; how to best manage land and forests; how to deal with and plan for drought; how to develop new crop varieties; and how to protect energy and public infrastructure.

## Geopolitical uncertainty

The growing importance of global supply chains has fundamentally changed the way the global economy and goods manufacturing are organised. For decades manufacturers have used increased globalisation and supply chains to drive efficiency and create lean manufacturing processes which have helped them grow and remain competitive. However, the Russian invasion of Ukraine, which has caused one of the greatest humanitarian crises in Europe since the Second World War, demonstrates the fragility of global supply chains to geopolitical events. In response to geopolitical uncertainty, Make UK found that over two-fifths of companies (42%) have increased their UK supply base, with over a quarter increasing supply from Western Europe, including Turkey [15]. A future vision might be more related to constraints around data supply chains (e.g. data storage and flows) instead of material/goods supply chains.

# 6.2.2. **WHAT BARRIERS TO ACHIEVING NET ZERO MANUFACTURING WERE IDENTIFIED?**

It is important to plan for potential barriers to implementation when assessing what manufacturing resilience improvements should be pursued by a manufacturer.

Previous identified financial weakness, lack of knowledge, unwillingness to share information and lack of flexibility among others [108]. During the Digitally Enabled Manufacturing Resilience Connected Everything roundtable, participants were asked to identify both current and future barriers to resilient manufacturing.

### Manufacturing complexity

Manufacturing systems and supply chains have become progressively more complex and inflexible. The inflexibility of manufacturing processes and supply changes makes it harder for manufacturers to respond quickly to disruptions. There are also sector-specific challenges that add complexities and complications to manufacturing supply chains. One example is the food and drink sector which contains a high number of perishable items with a short shelf-life (e.g. fruits, vegetables and fresh meat) and is reliant on reliable, efficient and predictable transportation links to ensure that goods reach their destinations as fresh as possible, reducing both food safety and waste issues.

All manufacturing systems contain inherent variation (e.g. fluctuations in process temperatures, pressure and flowrates, human operators, leakages) and managing this variability, to ensure a consistent product, can be very difficult.. For example, variability between nominally identical vehicles is an ever-present problem in automotive vehicle design, which can lead to customer dissatisfaction. Process manufacturing is subject to additional variability from within feedstock supply lines composition. The feedstock's physical and compositional variability can have a significant impact on the biochemical and thermochemical conversion to the final product. As manufacturers move away from non-renewable sources toward waste and biomass feedstocks, variability will become an even greater challenge for resilient manufacturing.

### Skills and knowledge

Manufacturers need access to the right skills across the workforce in order to evolve and adapt to disruptions. However, the Make UK 2022 survey found 'people, skills and training' to be the third most common factor inhibiting resilience [15]. At the level of individual workers, resilience is shaped by whether specific people can cope with disruptive changes such as redundancy, skills obsolescence and technological shifts. A resilient worker might be considered one with the capacity and willingness to retrain and acquire or update skills and even to exercise mobility to move geographically to new employment opportunities. Currently, there is a digital skills gap which is limiting the potential of digital solutions to increase a manufacturers' resilience.

### Ability to invest in resilience

The COVID-19 pandemic resulted in unprecedented supply-and-demand shocks, not only increasing the uncertainty of the economic outlook, but also affecting the financial and operational capacity of manufacturing and supply systems. Funding is available for innovation (e.g. Innovate UK), however, applying for funding is a time-consuming and costly process with no guarantee of success. For example, proposals for Innovate UK Smart Grants had an average success of less than 8% in 2021 [109]. From lower cash reserves and higher administrative costs to capital disruption and lack of traditional sources of financing, manufacturers have a reduced capability to invest in transforming their systems to become resilient. Realising this, the World Economic Forum and International Finance Corporation (IFC) have carried out a series of consultations with senior executives in operations and supply chains to explore and better understand financial needs in order to build resilience during and post-COVID-19 [110]. The consultations carried out revealed three main coordination imperatives for stakeholders looking to be better equipped in the event of future disruption:

1. A global mindset shift to first ensure sufficient financial liquidity for long-term resiliency investments
2. A shared vision, supporting the more fragile stakeholders in the path towards resiliency, starting with their suppliers and other important players along their value chains
3. New multistakeholder partnerships such as with academia and the public sector to finance increased resilience

### Availability of workforce during crisis

According to PwC, British manufacturers are facing the largest shortage of skilled workers since 1989, with many citing recruitment as their biggest challenge [111]. Manufacturing is a highly skilled industry that requires very specific qualifications from job applicants and makes hiring additional workers during a crisis challenging. Disruptions affects workers' mental health putting additional strain on the manufacturing workforce. For example, during the pandemic, workers in the manufacturing industries faced a wide range of challenges: frequent shutdowns and temporary layoffs and working long hours due to staffing shortages and consumer demands. At home, workers also faced unprecedented challenges, including school closings and caring for elderly loved ones. These issues are so widespread that one study by Glint showed an 86% spike in burnout among workers in the manufacturing industry during 2020 [112].

### Legacy equipment and processes

Traditionally, manufacturing processes and equipment are designed to have at least a 20-year lifetime. As a result, most of the equipment on-site will have been in operation for several years or decades and were never designed for 21st-century stresses (e.g. extreme weather events, net zero and circular economy thinking and move to resource recycling facilities, managing emerging pollutants and increasing waster demand). An example of this is wastewater treatment plants that are designed to remove contaminants from domestic and municipal wastewater. In recent years, concern has increased regarding the presence of many emerging contaminants at low concentrations within the water environment. Existing conventional water treatment plants were not designed for these emerging contaminants. Therefore, innovative approaches to wastewater treatment are required. Manufacturers need to recognise the need to upgrade their legacy equipment and processes to digitally transform their systems and use data to build future resilience.

### Reduced UK manufacturing capacity

The Make UK survey shows that UK manufacturers are aiming to bring back production to the UK in a "reshoring" drive to try to address the supply-chain disruptions caused by the coronavirus pandemic and Brexit [15]. However, the previous decades' worth of globalisation has reduced the UK's in-house manufacturing capacity. This presents practical challenges to UK manufacturers looking to reshoring, including:

- **Identifying suppliers:** The UK has lost visibility of the UK suppliers that can meet or adapt to suit requirements, meaning that finding, assessing and then contracting those potential suppliers will be a challenge for those looking to reshore. Digital technologies are enabling new initiatives to help improve the visibility of UK suppliers and manufacturing capabilities [100,113]
- **Lack of heavy industry:** The UK does not have the raw materials or infrastructure required for some industrial processes. It may be that the solution for some manufacturing businesses will be near-shoring; moving the manufacture of goods closer to home to reduce lead times and logistics, without actually fully returning to the UK [15].
- **Skills gap:** The manufacturing industry is struggling to attract, hire and retain talent for roles ranging from skilled production workers to R&D and digital manufacturing experts, to operational and business managers [48].

### Future unknowns

One of the main barriers is being able to quickly adapt to the unknown. Future pandemics, natural disasters, cyber-attacks and more could significantly alter consumer behaviour, supplies and manufacturing processes once again. During COVID-19, the most resilient companies were able to alter product lines to manufacture Personal Protective Equipment (PPE), face masks and other essentials to stay relevant. The ramifications of the UK existing the European Union are still unclear. Manufacturing accounts for around 10% of UK GDP, of which around half is reflected in EU export [114], and Brexit (combined with the severe challenges to UK manufacturing over the last decade or so brought about by rapid globalisation) brings both challenges around factors including regulatory frameworks, talent loss and movement, and increased tariff charges, as well as opportunities, such as disruption to supply chains and access to talent outside the EU. While not every manufacturer can or needs to change product lines so drastically, manufacturers should aim to achieve the agility that will serve them well in future crises.

## Climate change

As previously mentioned, climate change makes extreme weather more frequent and/or severe, it increases the probability of events that are more intense than manufacturing systems are constructed to withstand. Climate change and land-use change are projected to make wildfires more frequent and intense, with a global increase of extreme fires of up to 14 per cent by 2030, 30 per cent by the end of 2050 and 50 per cent by the end of the century, according to a new report by the UN Environment Programme [115]. Already in the UK, according to the National Fire Chiefs Council, this year alone England and Wales have had 442 wildfires, which compares with 247 last year [116]. While climate change will drive manufacturers to become more resilient, the uncertainty created by climate change will hinder manufacturers' efforts to achieve resilient supply lines and processes.

## Cyber security

As manufacturers progress through their digital transformation, cyber-attacks pose an increasing risk. In the UK and Ireland, manufacturing was the most targeted industry – accounting for 80% of all attacks in 2020 [117]. As manufacturers transition to more digitalised and interconnected systems and devices, they will face increasingly sophisticated cyber-attacks that are harder to prevent. Clearly, cyber security will become an increasingly important issue for manufacturers to protect their systems. However, security limitations may prevent access to alternative systems in other geographies and in the cloud, which may impede manufacturing resilience.

## Critical material shortage

Of the 118 elements that society relies on for getting from place to place, health, food supply, energy and communication, more than 40 are predicted to face supply limitations in the coming years (**Figure 6.3**). These critical elements include rare earth elements, precious metals, and even some that are essential to life, like phosphorus. Phosphorus is hardly uncommon and yet, through widespread use as phosphates in crop fertilisers, there is now a risk to future supply. Many reserves of rock phosphate are likely to be exhausted before the end of the century. Indium is another example of a rare metal used in television, computer and mobile phone flat-panel display screens and to dope silicon in microchip production. At the current rate of indium consumption, which is accelerating worldwide, supplies of indium ore could dwindle to nothing over the next 50 years. Research into more abundant alternatives, more efficient uses, value retention processes (e.g., recycling, remanufacturing, repair and refurbishment) and resource recovery will help mitigate risks and move the industry towards a sustainable and resilient supply of raw materials. Although remanufacturing, the highest value retention processes, is well developed in a few well-defined sectors (for example, the UK automotive and aerospace sectors had an estimated remanufacturing market of £16 billion in 2020) there is good potential in other areas as well, and this is not yet exploited [118]. There is evidence from manufacturers that reuse, repair, refurbishment could grow quickly if there were clearer coherence between the market and government policy and incentives [118].



## Competition with environmental sustainability

Environmental sustainability and resilience frequently overlap, and with good policy and planning reinforce one another. However, while they are highly related, they are not the same and may sometimes come into conflict with one another. For example, while renewable energy is clearly more environmentally sustainable than fossil fuel alternatives, it makes our energy systems increasingly sensitive to weather and climate variability and the possible effects of climate change. Scottish and Southern Energy (SSE) renewable assets produced 32% less power than expected between April and September 2021 as low wind speeds and dry conditions reduced wind and hydro output [120]. Conversely, some measures may be resilient but not environmentally sustainable. Engineered seawalls, as an example, will confer resilience to a shoreline, but often at the cost of interfering with sediment movement and build-up to the detriment of shoreline habitat. Looking forward to 2050, achieving both environmental sustainability and resilience will remain a key goal for manufacturers. Understanding how these two terms interact will help manage those interactions and the trade-offs that may arise.

## Policy

In recent years, various countries have brought in a range of measures with a focus on enhancing the resilience of supposedly strategic sectors, but some of these policies have been introduced to protect domestic industry from foreign competition. The UK Trade Policy Observatory outlines the risk that supply chain resilience is used as a get-out clause for a wide range of industrial policy interventions to disguise protectionism [121]. Protectionism often undermines resiliency by weakening a country's economy and manufacturing sector. For example, International Monetary Fund economists in 2018 examined data for 151 countries over 51 years (1963–2014) and found that "tariff increases lead, in the medium term, to economically and statistically significant declines in domestic output and productivity" as well as more unemployment and higher inequality [122].

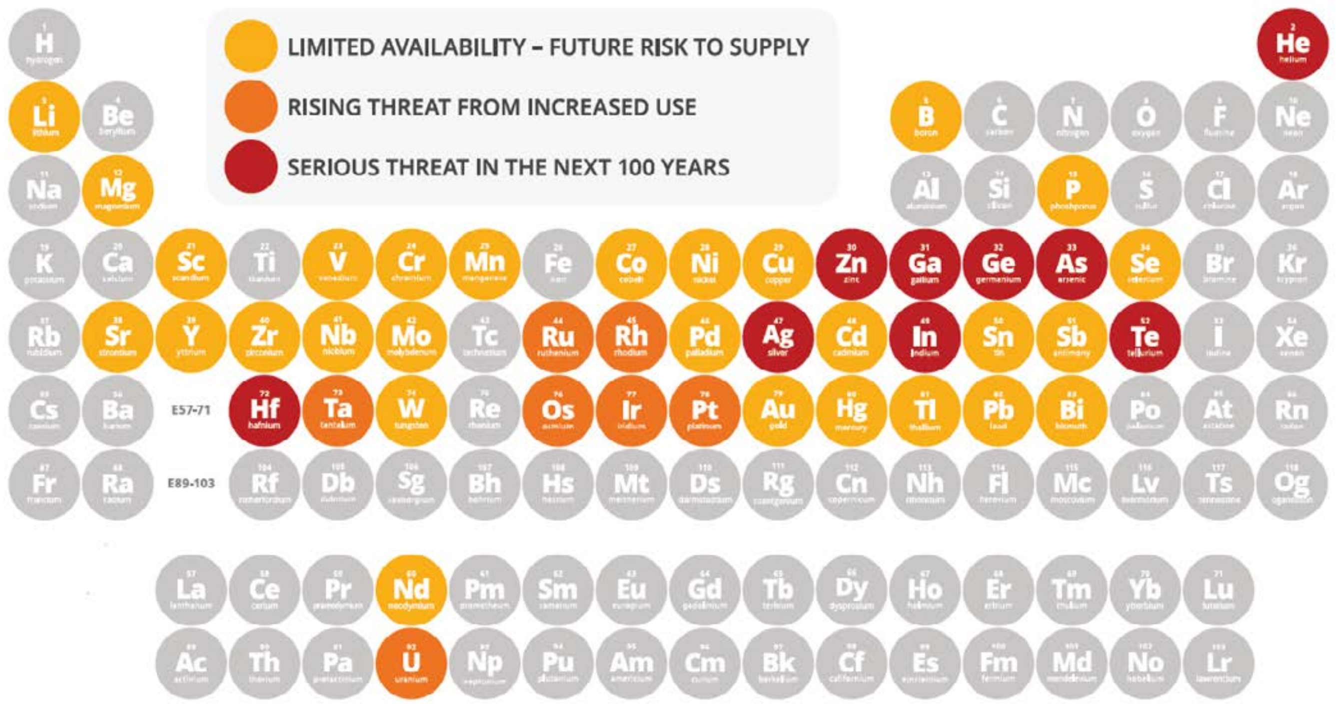



**Figure 6.3**
The periodic table of endangered elements. Sourced from the American Chemical Society [119]

# 6.3. HOW CAN DIGITAL TECHNOLOGIES ENHANCE RESILIENCE?

There is risk in assuming that the digital transformation will automatically lead to resilience.

However, technology itself will not realise resilient manufacturing. Understanding how to best apply and utilise existing techniques and innovation will be key. From the roundtable discussion, six clear ways by which digitisation can help manufacturers become more resilient emerged (**Figure 6.4**)


**Figure 6.4**
Uses of digital technologies to support resilient manufacturing

## Agile manufacturing systems

Manufacturing systems need to become agile to swiftly respond to shocks that interrupt normal operations. Agile manufacturing is a manufacturing methodology that has existed since the 1990s and lays out the processes and tools that help companies rapidly respond to changes in the marketplace without increasing costs or sacrificing quality. Digital manufacturing offers means to strengthen agile manufacturing by enhancing flexibility. Example applications of industrial digital technologies to increase resilience include:

- **Industrial internet of things:** Devices connected to the internet enable organisations to have an integrated information system in support of supply chain operations and visibility, and, in turn, flexibility and decreasing of responding to customer or market requirements.
- **Reprogrammable robotics:** Automation and robotics can become agile and reprogrammable through new algorithms that can automatically generate programme and configuration data from CAD and process data speeding the time to respond.
- **Additive Manufacturing (AM):** The additive nature of the AM process allows for the fabrication of complex geometries, which, unlike traditional subtractive manufacturing methods, do not require specialist tooling. Production can switch from one part to another almost instantly, which has been demonstrated by those with addivtive manufacturing capabilities producing products on demand.
- **Blockchain:** Blockchain technologies could offer provenance to big data within supply chains, capturing data regarding products, services and supply chain tiers in real-time, thereby enhancing supply chain agility.
- **Cloud manufacturing:** The cloud manufacturing model is the concept of sharing manufacturing capabilities and resources on an intelligent cloud platform. By nature cloud manufacturing production lines are no longer fixed but temporary, allowing for the option of small or long production runs depending on user and market demands. The supporting supply lines are highly reconfigurable, dynamic and agile giving cloud manufacturing the ability to adapt to unpredicted changes of circumstance.
- **Factory in a box:** A factory in a box is a rapidly deployable, remotely managed, modular manufacturing supply chain network enabled by industrial digital technologies. It is a rapid route to market for products with a faster return on investment on its manufacturing innovation and new disruptive business models for the supply chain.

## Fail faster, learn faster

The "fail fast, fail often" mantra has been the foundation for innovative companies. With fail fast, fail often there is a clear link between failure and innovation, rapidly turning small mistakes into creativity and iteratively building resilience. However, recent thinking has highlighted that this mantra has become outdated as technology has matured and there is more opportunity to learn from successful innovations [123]. Digital manufacturing can support this by providing manufacturers with the tools needed to create digital infrastructure and simulation capabilities to evaluate different configurations, and assess limits of flexibility and elasticity (i.e., the ability for a manufacturer to increase/decrease volume and product mix). For example, adopting sophisticated modelling techniques, such as digital twin technology, can help manufacturers replicate ideas quickly and help identify and reduce potential risks.

Rapid prototyping is a group of techniques used to quickly fabricate a scale model of a physical part or assembly using three-dimensional computer-aided design data. The advent of rapid prototyping has not only made it easier for manufacturing companies to create a scaled model of their products, but also to test those products and easily make changes to the prototype. The Ventilator Challenge in the UK has shown that it is possible to rapidly produce very precise and highly regulated products by using digital technologies to speed up collaboration across manufacturers and sectors. Immersive technologies provided a crucial part of collaborative efforts throughout the design and production of ventilators across multiple sites, from the development of a digital twin of the production sites at the start of the process through to training over 3,500 employees via augmented reality. The ability of digital technologies to support rapid prototyping allows manufacturers to quickly respond to changing market conditions.

### Case Study 10: Manufacturing of 3D-printed morphing origami solar sails for the next generation of CubeSats

**Project Partners:** University of Liverpool, Oxford Space Systems, Japan Aerospace Exploration Agency

**Background**
Currently, spacecraft deployable structures (i.e. solar arrays, antennas, etc.) are deployed in-space utilising origami-based designs. However, all such large devices are designed to maintain a fixed-shape once deployed and a single spacecraft usually mounts multiple structures for different purposes.

**Digital Manufacturing Application**
The project explored Additive Manufacturing (AM) techniques to prototype a new morphing origami solar sail mechanism for next generation of self-reconfigurable CubeSats. The use of AM and rapid prototyping enabled the investigation a variety of candidate materials for the OrigamiSat folding mechanism and membrane.

**Outcomes**
This project demonstrated the feasibility of a new generation of origami solar sail's membranes that make use of 3D printable polymers and 4D shape memory polymers on a high reflectivity material to enable reconfigurability. The sail is deployed in space by harnessing the Solar Radiation Pressure through Polymer Liquid Crystal Devices, which are capable of changing local reflectivity and therefore create a torque for the autonomous deployment.

## Supply chain transparency

Supply-chain resilience for manufacturers comes from having the data and insight to make well-informed decisions as early as possible. With a diverse and secure supply chain in place, this gives the agile the ability to move nimbly to respond to change and uncertainty. However, the Make UK 2022 survey of manufacturers highlighted visibility as being needed for early identification of vulnerability and mitigation of risk through a supply chain resilience review [15]. Most manufacturers already know who their critical suppliers are, but they do not always know who their suppliers' suppliers are, which introduces a significant but hidden vulnerability in their supply chains.

In the past, having this level of visibility would have been impossible, yet increasingly the digital transformation is creating data systems that allow manufacturers to measure, track and reflect on the entire value chain. For example, initiatives from Value Chain and Reshoring UK have created digital portals to help improve the visibility of UK suppliers and manufacturing capabilities [100,113]. From the Internet of Things sensors on everything from shipping containers to factory machinery to artificial intelligence-powered analytics, and cloud computing providing the storage it all requires, the technology is available to gather, sort, analyse and draw insights from vast amounts of data that a multi-faceted supply chain generates. In the future emerging manufacturing paradigms, like cloud manufacturing, can use these technologies to monitor data across the supply chain identify coordinate and implement opportunities for increased resilience. This provides an infrastructure that can quickly respond to consumer and producer requirements and minimise energy, transport, materials and resource usage while maximising environmental sustainability, safety and economic competitiveness [124]. This could not have been realised by the current manufacturing model where enterprises within a supply chain act with greater independence from each other.

## Predictive resilience

Increasing resilience through the use of demand forecasting on the needs of partners and suppliers was selected as the top attribute manufacturers wanted to see from the supply chain in 2021, with nearly 60% putting it at number one or number two [15]. This is not surprising as accurate forecasting relates almost directly to building resilience. Digital manufacturing technologies, such as AI and machine learning, the Industrial Internet of Things and 5G, will enable a data-driven approach that will give us better awareness to take action on or compensate for unanticipated problems. The idea is ultimately to use the information to circumvent problems as they emerge, or preferably, anticipate them well before.

Machine learning has the ability to automate analysis and detect patterns of data at a rate that would be impossible for humans to achieve. It can take data segmentation beyond simple keyword clusters and opens up the opportunity to glean information from new data sources. When applied to forecasting models, machine learning models can predict the future and warn of events that are going to happen so manufacturers can take corrective actions. According to Mckinsey Digital, machine learning-powered forecasting can reduce errors by 30 to 50% in supply chain networks [125].

### Case Study 11: Digital Twins to Protect Wind Turbines

**Project Partners:** University of Nottingham and Whitwell

**Background**
Serve winds can result in damage to wind turbines. As wind speeds increase, more electricity is generated until it reaches a limit, known as the rated speed. This is the point that the turbine produces its maximum, or rated power. As the wind speed continues to increase, the power generated by the turbine remains constant until it eventually hits a cut-out speed (varies by turbine) and shuts down to prevent unnecessary strain on the motor.

**Digital Manufacturing Application**
Using algorithms built on GE's software platform for the industrial internet and a modelling approach developed by Ansys, a leader in engineering simulation software, these engineers use "digital twin technology" to digitally play out different scenario. They the use the insights gained from these tests to maximise output and minimise downtime by spotting problems before they lead to an unplanned outage.

**Outcomes**
Developed a digital twin of the Haliade 150-6 wind turbine's yaw motors which was used to monitor how the motors perform under different strains over time and learn more about operating them at peak efficiency. This enabled the 6-megawatt turbine to rotate and position itself into the wind to boost the performance and avoid outages.

## Collaborative resilience

Digital manufacturing integrates technology and human strengths of problem-solving, value-adding creativity, and deep understanding of customers, to improve products and productivity and enable mass personalisation. Future manufacturing systems should be designed to capitalise on this to ensure human operators are performing tasks they excel at, while digital technologies and machines are applied to complete manufacturing tasks they excel at. Most manufacturing errors occur when system design allows human error to occur. There is an opportunity to address poorly designed manufacturing and enable humans and machines working alongside each other to enhance each other's strengths (**Figure 6.5**). To take full advantage of this collaboration, manufacturers must understand how humans can most effectively augment machines, how machines can enhance what humans do best, and how to redesign manufacturing systems to support the partnership.

With the rise of digitisation, the possibility of the occurrence of new types of manufacturing failures. Therefore, human observation, or human-in-the-loop, will become more important to provide supervisory oversight of critical information flows and remains an active participant in the delivery of the next generation of production systems.



### Case Study 12: Long-term Performance Monitoring using Fibre Optic Sensors

**Project Partners:** University of Nottingham and Whitwell

**Background**
Safety and performance of their service network is therefore a key priority for Network Rail. Remote monitoring has several benefits over using human inspectors alone. Sensors reduce the subjectivity of monitoring. Factors such as light levels, weather and variations in alertness can change the subjective assessments made by human inspectors. They may also be able to identify issues arising before visual inspection can detect them by monitoring the stresses on the bridge. A human inspector will still be sent to site to follow up on what the remote sensing has indicated, and engineers will of course still need to perform maintenance. However, remote monitoring allows the asset owners to be smarter about how these human resources are deployed.

**Digital Manufacturing Application**
The digital twin of the Staffordshire Bridges centres on a physics-based model for conducting structural analysis and load-carrying capacity assessments. The site-specific information, such as realistic loading conditions obtained by the sensors, will be fed into the physics-based model to simulate the real structure and provide the outputs of interest. A digital twin replica of the structure will be able to provide bridge engineers with any parameter of interest anywhere on the structure, including in non-instrumented locations.

**Outcomes**
Working with Network Rail, this project demonstrated the use of real-time data analytics integrated with digital twins to provide useful information to support engineers and asset managers to schedule proactive maintenance programmes and optimise future designs, increasing safety and reliability across their whole portfolio of assets.

**Collaborative Intelligence**
Through such collaborative intelligence, humans and AI actively enhance each other's complementary strengths. The leadership, teamwork, creativity, and social skills of the former, and the speed, scalability, and quantitative capabilities of the latter [126]. Looking forward to 2050, collaborative intelligence may free the manufacturing workforce from mundane, repetitive tasks in order to focus on more high-value and/or creative tasks.

**Augmentation**
Manufacturing work has a high intrinsic difficulty and traditional workflows and tools increase can the cognitive load on workers. Augmentation technologies have the ability to minimise the effects of stress and time pressure, by integrating workers into the manufacturing environment to enhance a worker's abilities. This brings many variables outside of workers' control under management. For example, interactive digital work instructions can help reduce cognitive load by guiding workers through complex processes.

**Figure 6.5**
Opportunities to improve manufacturing systems by integrating digital technologies within the workforce

### Unlocking sustainable resources

The circular economy model, which focuses on extending product lifetime, regeneration, restoration and re-use at all stages of a resource's life cycle, has been proposed to keep critical raw materials within the economy and ensure future resource security. However, it is not possible to reach a fully circular economy, as the process of recycling will always create waste and side products. Instead, the goal is to identify resources from renewable sources and to minimise the spent resource leaving the system. With more and more businesses adopting technology to boost efficiency and drive productivity, technology can also be an enabler in unlocking the possibility of new renewable resources in new markets. Digitisation enables the efficient use of data for designing and implementing circular solutions and utilising side streams/by-products. One such application is the development of data-driven models to describe manufacturing systems and enable intelligent decision-making on cloud platforms like Sharebox (a platform for physical resource sharing) [127]. By sharing and modelling a manufacturing system's data, a data-driven model may evaluate the economic feasibility and environmental impact of utilising one manufacturer's by-products (including energy, water, logistics and materials) as a resource for another [128]with related cradle-to-cradle implications requiring implementation from the design stage. The challenge lies in moving manufacturing environments away from the traditional linear economy paradigm, where materials, energy and water have often been designed to move out of the system and into receivership of waste management bodies after use. Recent applications of industrial digital technologies (IDTs: for example internet of things, data-driven modelling, cyber-physical systems, cloud manufacturing, cognitive computing.

Biomanufacturing, which utilises biological systems to produce commercially important biomaterials and biomolecules plays an important role in moving away from non-renewable resources, and has shown successful applications in manufacturing electronic components (e.g. bio-based flexible printed circuits), fine or speciality chemicals (e.g. bio-lubricants), building and construction (e.g. biocementation), consumer products (e.g. bio-based detergents), food (e.g. vitamin and amino acid fortification) and pharmaceuticals (e.g. vaccine production). However, current biomanufacturing routes emit large amounts of $CO_2$ and only convert two-thirds of carbon resource flows into products [129]. Digital twins of these systems may be developed to serve as real-time predictive/decision-making tools to self-optimise unit operations to capture, formulate and emulate the dynamics of the manufacturing systems within appropriate interoperable constructs, rules and algorithms that are accurate representations of highly interlinked products, processes, lifecycles and supply chains.

# 6.4. CHALLENGES AND RISKS FROM DIGITISATION

While digitisation proposes opportunities for manufacturers to become more resilient, it also introduces several challenges and risks.

The Connected Everything roundtable discussion, highlighted ten potential risks and challenges that are summarised in **Figure 6.6**.



**Data sharing across the value chain**
Greater communication and the coordination of data means that the entire value chain becomes more efficient, mitigating potential future disruptions. However, exchanging data successfully requires overcoming both technical and trust-based barriers [17].

**Modelling complex systems**
Certain digital manufacturing solutions (e.g. digital twins) are dependent on modelling manufacturing systems (i.e., processes and materials). It is challenging to model a system when there is limited knowledge/data of the underlying system. This is made worse for systems that experience a high level of variability in their processes and materials.

**Time to invest properly**
Technology adoption is driven by exploring opportunities to innovate. Manufacturers, particularly SMEs, are time-poor which limits their ability to perform root cause analysis to identify areas that need improving.

**Digital solutions prioritising productivity**
Success is still measured in terms of growth, which is not necessarily complementary to resilience. Therefore, industrial digital technologies are often deployed to maximise productivity, lower energy costs and increase competitive advantage.

**Compliance with regulation**
Failure to comply with statutory requirements, including technology laws, sectoral laws and environmental regulations, risks increasing as they become increasingly complex in order to keep pace with digitisation.

**Cost to digitalise**
The recent pandemic has had a profound impact on manufacturers' finances, and one third of manufacturers expect the situation to worsen [16]. This lack of finance is deterring manufacturers' willingness to invest in digital manufacturing.

**Process manufacturing vs discrete manufacturing**
The two branches have distinct differences (e.g. processes, materials and products) and while digital manufacturing can work for both, we need to understand both branches' specific challenges and requirements.

**Incorrect application of a digital solution**
The risk from assuming digital will automatically improve resilience, as opposed to proactively building resilience. We cannot 'fix' resilience through digitisation, but can use it is an enabler to provide better knowledge to adapt. Also, we need to be wary of limited digital experience that can lead to incorrect use (e.g. automating wasteful activity).

**Digital vulnerabilities**
As manufacturers undergo a digital transformation of their assets, the threat of cyber-attacks and risks to data privacy increase. Furthermore, risk of disruptions in operations or unavailability of manufacturing capabilities or services due to high dependency on tightly coupled technology.

**Lack of trust in digital manufacturing**
Heavy reliance on digital technology and systems that are not fully understood by users can erode digital trust. When making changes to improve resilience, manufacturers need to be able to understand decision reasoning. However, many digital solutions are suggested via black-box modelling (i.e. models whose processes are unknown), which lack explainability.

**Figure 6.6**
Digital manufacturing challenges and risks

# 6.5. CONCLUSION AND RECOMMENDATIONS

The magnitude of recent disruptions to everyday manufacturers has brought resilience to the head of strategic agendas. However, there are numerous barriers, from manufacturing complexity to cost, that are preventing manufacturing from becoming resilient to these disruptions. Moving towards 2050, we expect other barriers to emerge as resilience competes increasingly with sustainability and the effects of climate change and diminishing natural resources. While digital manufacturing offers a route forward toward achieving resilient manufacturing, it requires a coordinated effort from industry leaders, researchers and policy setters to achieve. This study highlights six methods of using digital technologies for manufacturers to continue towards resilient manufacturing.

**Adaptable manufacturing systems:** Digital manufacturing offers the means to strengthen agile manufacturing by enhancing flexibility. Industrial digital technologies including the internet of things, reprogrammable robotics, cloud manufacturing and factory in a box can be used to increase resilience.

- **Fail faster, learn faster:** Digital manufacturing can support fail faster, and learn faster by providing manufacturers with the tools to create digital infrastructure and simulation capabilities to evaluate different configurations, and assess limits of flexibility and elasticity (i.e., the ability for a manufacturer to increase/decrease volume and product mix).
- **Supply chain transparency:** The digital transformation is creating data systems that allow manufacturers to measure, track and reflect on the entire value chain. Data across the supply chain can identify, coordinate and implement opportunities for increased resilience.
- **Predictive resilience:** Digital manufacturing technologies, such as AI and machine learning, Industrial Internet of Things and 5G, will enable a data-driven approach that will give us better awareness to take action on or compensate for unanticipated problems.
- **Collaborative resilience:** Manufacturers must understand how humans can most effectively augment machines, how machines can enhance what humans do best, and how to redesign manufacturing systems to support the partnership.
- **Enabling new resources:** Digitisation enables the efficient use of data for designing and implementing circular solutions and utilising side streams/by-products.

The ability of digital manufacturing to increase manufacturing resilience will depend on the policy decisions we make today, and the actions of governments, industry and funders. From the Connected Everything roundtable discussion we make six recommendations to guide resilient manufacturing future research agendas and policy, which are summarised in **Figure 6.7**.



**Translate expertise into business**
In order to maximise digital manufacturing potential, the right people, with the right skills need to be in the right place. Therefore, more support for initiatives that translate digital expertise into the business is required.

**Consolidate and simplify resilience guidance**
Manufacturers seeking to increase their resilience are exposed to many sources of, sometimes conflicting, advice about where to start. Formation of a national platform that consolidates the resilient manufacturing guidance and expertise is required.

**Support waste as viable alternative resource**
Many of the current resources (materials, rare earth metals and water) manufacturers rely on will soon be facing supply limitations. More support is required to enable the exchange of complex materials (e.g. spent resources), as current legislation exists that can limit waste valorisation opportunities.

**SME resilience funding**
Additional funding and an adapted fiscal and financial landscape to incentivise resilient investment, even if this leads to higher-cost processes and products.

**Measure and evaluate policies' impact**
Previous policies have caused unintended consequences that have harmed resilience. Other well-regarded policies have been unexpectedly cancelled. When setting up future policies and programmes, need to define measures of success and monitor them to understand what has and has not worked.

**Forward thinking policies**
Resilient manufacturing solutions will exploit several levels of technology integration and increased collaboration across the value chain. Forward thinking policies to support this transition are required that avoid recent trends toward protectionism.

**Figure 6.7**
Recommendations from roundtable discussion to support manufacturers achieve resilient manufacturing

# 7. CONCLUSION

In the last few years, the economic environment in which manufacturers are now operating in has dramatically changed. With seismic changes in the UK economy's situation following the UK's exit from the European Union (EU), global pandemic and war in Ukraine. This poses risks to innovation by shifting resources towards protecting against the uncertainty of the immediate future rather than taking on risks that may better society and the UK's growth. The manufacturing sector must be forward thinking, bold, and innovative if the UK is to remain one of the world's leading manufacturing nations.

Digital technology is becoming embedded throughout manufacturing and society, so it has a critical and growing part to play in addressing manufacturing challenges and delivering a sustainable and resilient future. During this study the challenge to define what is the boundary of the manufacturing sector emerged. Some of the examples and cases studies raised by the contributors to this 2050 study demonstrate the application of digital technologies within specific manufacturing silos (e.g. self-optimising clean-in-place of food and drink processing equipment), while others present a vision of manufacturing as part of a broader societal and industrial shift, instead of a "group of companies". As digital technology continues to create a more connected world, we envision the manufacturing sector boundary to become increasing blurred and manufacturing and society to become increasingly linked.

Maximising digital technology's contribution will depend on the decisions we make today, and the actions of governments, industry and funders. A total of 27 recommendations emerged from the Connected Everything digital manufacturing 2050 study including: encouraging researchers to quantify digital solution impact; supporting the design of sustainable products; providing financial incentives for manufacturers to decarbonise; and removing legislation preventing waste from being used as a viable alternative resource. Across the four themes, five recommendations emerged strongly and consistently:

- **Connect digital technology developers to manufacturers:** Greater support is needed to connect manufacturing businesses with the UK innovation community, creating opportunities, increasing productivity and solving industry challenges. This will ensure future digital manufacturing research will develop solutions that fit manufacturing priorities.
- **Reduce digital manufacturing knowledge barriers:** Digital manufacturing solutions need to become as simple and intuitive to use as installing a new mobile phone app or using a self service checkout. An example of this is the no-code revolution that allows anyone to create software through more intuitive visual interfaces. This helps put the power to design flexible, scalable, customisable applications in the hands of manufacturing experts.
- **Consolidate digital manufacturing guidance:** Manufacturers seeking digital manufacturing guidance are exposed to many sources of, sometimes conflicting, advice about where to start. More signposting to initiatives like Made Smarter and Knowledge Transfer Network is needed to help manufacturers access the expertise required to implement digital manufacturing solutions.
- **Support employee wellbeing during transition:** Digitisation may lead to employee anxiety from the uncertainty of future job security and demand for reskilling. Communicating clearly and consistently with employees about how the opportunities digitisation offers them can help people engage with the digital transformation and not be left behind.
- **Transparency of value chain data:** To enable many digital manufacturing solutions will require transparency of supply chain data (e.g. emissions). Support to improve data sharing and transparency is needed to understand the environmental and social impact of manufacturing decisions, to drive more sustainable choices.

# ABOUT THE AUTHORS

**Oliver Fisher** has a MEng in Chemical Engineering (University of Nottingham, UK, 2016) and a PhD in Chemical Engineering (University of Nottingham, UK, 2020). Following Oliver's PhD he was a awarded a postdoctoral prize fellowship to undertake research improving resource security within food and agricultural systems using digital technologies. Oliver then started a research fellow and knowledge exchange lead for the Connected Everything Network Plus where he splits his time between leading multiple digital manufacturing research projects and managing network plus's science communication strategy.

**Okechukwu Okorie** currently a Lecturer (Assistant Professor) in Sustainable Manufacturing in the College of Engineering, Mathematics and Physical Sciences (CEMPS) at the University of Exeter. He was formerly a Senior Research Fellow at the Exeter Centre for the Circular Economy, University of Exeter. His research concerns digitally enabled remanufacturing in operations and supply chains, as well as developments of novel circular business models and solutions for more sustainable, resilient and better performing manufacturing processes, products and services. He was a Visiting Scholar in Remanufacturing at the Golisanno Institute of Sustainability, Rochester Institute of Technology, New York. He completed a PhD at the Sustainable Manufacturing Systems Centre, Cranfield University and has been a lead researcher/ PI/ Co-PI of several funded grants. He has published over 15 articles in the areas of digitalisation, the circular economy, sustainability research, remanufacturing and simulation modelling as well as winning 2 conference-based awards. He is a UK IMechE Chartered Engineer.

**Fiona Charnley** is Professor of Circular Innovation within the Business School at the University of Exeter. She is Co-Director of the UKRI National Interdisciplinary Circular Economy Hub, which aims to harness and scale-up the UK's leading research capabilities, providing the evidence base, inspiration, and capacity to accelerate the transition towards a global circular economy. Fiona leads a number of government and industry-funded research projects covering topics such as the use of digital technology to inform decisions surrounding the implementation of circular economy strategies and the development and application of self-healing materials to enable product life extension. Fiona has extensive experience of working with organisations from across sectors to identify new approaches to design, innovation, manufacture and business modelling to transform resource use and value creation. She has also led multiple education and executive training programmes to support future leaders in developing the skills and capabilities necessary to transform our industrial system.



# ABOUT CONNECTED EVERYTHING

Connected Everything is an EPSRC funded research Network Plus for the Digital Manufacturing community which is addressing the question 'how do we support the future of manufacturing in the UK?' The Connected Everything network represents a broad range of disciplines, including manufacturing computer science, cybersecurity, engineering, human factors, business, sociology, innovation and design. The network aims to accelerate multi-disciplinary collaboration, foster new collaborations between industry and academia and tackle emerging challenges which will underpin the UK academic community's research in support of people, technologies, products and systems for digital manufacturing. Through a range of activities, including feasibility studies, networking, and thematic research, Connected Everything brings together new teams within a multidisciplinary community to explore new ideas, demonstrate novel technologies in the context of digital manufacturing, and accelerate impact of research into industry.

The Connected Everything Project Team includes:

- Professor Sarah Sharples, Department of Transport and University of Nottingham (Principal Investigator)
- Professor Duncan McFarlane, University of Cambridge
- Professor Fiona Charnley, University of Exeter
- Dr Peter Green, Engineering Data Analytics and University of Liverpool
- Dr Nik Watson, University of Nottingham

## Details of Editors

- Professor Sarah Sharples, Chief Scientific Adviser for Department of Transport, Professor of Human Factors at University of Nottingham
- Dr Peter Green, Director of Engineering Data Analytics, Senior Lecturer at University of Liverpool
- Susan Reiblein, Manufacturing consultant
- Dr Alejandro Veliz Reyes, Associate Professor at University of Plymouth

## Details of Reviewers

- Professor Duncan McFarlane, Professor of Industrial Information Engineering at Cambridge University
- Dr Nik Watson, Associate Professor at University of Nottingham
- Dr John Oyekan, Lecturer at University of Sheffield
- Professor Cinzia Giannetti, Professor in Mechanical Engineering at Swansea University
- Emma McLeod, Senior Research Fellow at Mondelez International
- Ben Peace, Director of Sustainability at Valuechain Technology Ltd.

# LIST OF ROUNDTABLES

**Roundtable:** Digital Support for Achieving Net Zero Manufacturing by 2050

**Chair:** Fiona Charnley, University of Exeter

**Date:** 13/05/2021

**Attendees:**

- Paul Clarke, GKN
- Sam Turner, HVMC
- Martin Miller, Allied Bakeries
- Saeema Ahmed-Kristensen, University of Exeter
- Martin Aston, Forvanda Ltd.
- Barry Waddilove, Electrolux
- Andrew Clifton, Rolls-Royce
- Hao Dinh, Electrolux
- Roger Maull, University of Exeter
- Richard Kenny, Techbuyer
- Sarah Sharples, Department for Transport & University of Nottingham
- Kevin Towers, Techbuyer
- Ashutosh Tiwari, University of Sheffield
- Oliver Fisher, University of Nottingham
- Okechukwu Okorie, University of Exeter
- Debra Fearnshaw, University of Nottingham

**Roundtable:** Digitalisation and The Manufacturing Workforce of the Future

**Chair:** Sarah Sharples, Department for Transport & University of Nottingham

**Date:** 13/01/2022

**Attendees**

- Fiona Charnley, University of Exeter
- Stuart Fenton, Smart Wireless Innovation Facility
- Abigail Hird, KTN
- Paul Shakspeare, High Value Manufacturing Catapult
- Neil Mansfield, Nottingham Trent University
- Jordan Jenkins, University of Wales Trinity Saint David
- Robert Houghton, University of Nottingham
- Oliver Fisher, University of Nottingham
- Richard Morgan, University of Wales Trinity Saint David
- Debra Fearnshaw, University of Nottingham Sue Daley, techUK

**Roundtable:** Industrial Digital Technologies in 2050

**Chair:** Nik Watson, University of Nottingham

**Date:** 18/01/2022

**Attendees**

- John Oyekan, University of Sheffield
- Gary Punter, University of Cambridge
- Adam J Sobey, University of Southampton
- Peter Green, Engineering Data Analytics Ltd & University of Liverpool
- Emma McLeod, Mondelēz International
- Cinzia Giannetti, Swansea University
- Ken Lewtas, Lewtas Science & Technologies Ltd.
- Oliver Fisher, University of Nottingham

**Roundtable:** Digitally Enabled Manufacturing Resilience

**Chair:** Fiona Charnley, University of Exeter

**Date:** 25/01/2022

**Attendees**

- Duncan McFarlane, University of Cambridge
- Alejandro Veliz Reyes, University of Plymouth
- Rachel Gomes, University of Nottingham
- Justyna Rybicka, Manufacturing Technology Centre
- Ben Peace, Valuechain
- Michael Groves, Topolytics
- Darius Danaei, University of Cambridge
- Jeanne Blanchard, University of Southampton
- Kerry Whiteside, Samworth Brothers
- Oliver Fisher, University of Nottingham
- Steven Furnell, University of Nottingham
- Debra Fearnshaw, University of Nottingham
- Andrew Cusick, DXC Technology



# REFERENCES


[1] Oxford Economics, The true impact of UK manufacturing, Oxford, 2018. https://www.mta.org.uk/system/files/resource/downloads/20180405 MTA report - final v2.pdf (accessed September 28, 2019).

[2] The Digital Economy and Society Index (DESI) | Shaping Europe's digital future, (n.d.). https://digital-strategy.ec.europa.eu/en/policies/desi (accessed June 14, 2022).

[3] Department for Business Energy & Industrial Strategy, Made Smarter Review 2017, London, UK, 2017.

[4] Digital Manufacturing Technologies | High Value Manufacturing CatapultHigh Value Manufacturing Catapult, (n.d.). https://hvm.catapult.org.uk/digital-manufacturing/ (accessed June 14, 2022).

[5] Reinhard Geissbauer, Stefan Schrauf, Philipp Berttram, Farbound Cheraghi, Digital factories 2020: Shaping the future of manufacturing , 2020. https://www.pwc.de/de/digitale-transformation/digital-factories-2020-shaping-the-future-of-manufacturing.pdf (accessed June 14, 2022).

[6] Ewelina Gregolinska, Rehana Khanam, Frédéric Lefort, Prashanth Parthasarathy, Industry 4.0: Digital transformation in manufacturing | McKinsey, 2022. https://www.mckinsey.com/business-functions/operations/our-insights/capturing-the-true-value-of-industry-four-point-zero (accessed June 14, 2022).

[7] Digital Engineering | Manufacturing Technology Centre, (n.d.). https://www.the-mtc.org/what-we-do/technologies/digital-engineering/ (accessed June 14, 2022).

[8] Institute for Manufacturing, Application of digital technologies to innovation in manufacturing, 2020. https://www.ifm.eng.cam.ac.uk/insights/digital-manufacturing/application-of-digital-technologies-to-innovation-in-manufacturing/ (accessed June 14, 2022).

[9] E. Börje, J. Rockström, World Economic Forum, Digital technology can cut global emissions by 15%., (2021). https://www.weforum.org/agenda/2019/01/why-digitalization-is-the-key-to-exponential-climate-action/ (accessed August 22, 2022).

[10] Harnessing the Fourth Industrial Revolution for Water, 2018. https://www.weforum.org/reports/harnessing-the-fourth-industrial-revolution-for-water (accessed August 22, 2022).

[11] Future of Food : Harnessing Digital Technologies to Improve Food System Outcomes, World Bank, Washington, DC, 2019. doi:10.1596/31565.

[12] M. Neal, G. Skye, World Economic Forum, The 5 inequalities in health digital tech can address, (2021). https://www.weforum.org/agenda/2021/09/how-digital-technologies-can-address-5-sources-of-health-inequity/ (accessed August 22, 2022).

[13] S. Dutta, B. Lanvin, The network readiness index 2021, 2021.

[14] MAKE UK, Innovation Monitor 2020, 2020.

[15] MAKE UK, Infor, Operating without Borders – Building Global Resilient Supply Chains, 2022.

[16] MAKE UK, Executive survey 2021, 2021.

[17] World Economic Forum, Share to Gain: Unlocking Data Value in Manufacturing, Switzerland, 2020. https://www3.weforum.org/docs/WEF_Share_to_Gain_Report.pdf (accessed May 24, 2022).

[18] Department for Education, Lifelong Loan Entitlement Government consultation, 2022.

[19] P. Kerdlap, J.S.C. Low, S. Ramakrishna, Zero waste manufacturing: A framework and review of technology, research, and implementation barriers for enabling a circular economy transition in Singapore, Resour. Conserv. Recycl. 151 (2019) 104438. doi:10.1016/J.RESCONREC.2019.104438.

[20] European Environment Agency, Circular by design - Products in the circular economy , 2017. https://www.eea.europa.eu/publications/circular-by-design (accessed August 23, 2022).

[21] UK statistics on waste - GOV.UK, (n.d.). https://www.gov.uk/government/statistics/uk-waste-data/uk-statistics-on-waste (accessed May 26, 2022).

[22] Index of Production, UK - Office for National Statistics, (n.d.). https://www.ons.gov.uk/economy/economicoutputandproductivity/output/bulletins/indexofproduction/march2022 (accessed May 26, 2022).

[23] Energy consumption in the UK 2021 - GOV.UK, (n.d.). https://www.gov.uk/government/statistics/energy-consumption-in-the-uk-2021 (accessed August 24, 2022).

[24] The Guardian, Limits on renewables 'will keep UK energy bills higher this winter' | Renewable energy | The Guardian, 2022. (n.d.). https://www.theguardian.com/environment/2022/may/24/limits-on-renewables-will-keep-uk-energy-bills-higher-this-winter (accessed August 23, 2022).

[25] World First as 100% Hydrogen Glass Fired at Pilkington UK | Off Grid Energy Independence, (n.d.). https://www.offgridenergyindependence.com/articles/24636/world-first-as-100-hydrogen-glass-fired-at-pilkington-uk (accessed May 26, 2022).

[26] HM Government, UK Hydrogen Strategy, 2021. www.gov.uk/official-documents (accessed August 23, 2022).

[27] M. Aziz, A. Darmawan, F.B. Juangsa, Hydrogen production from biomasses and wastes: A technological review, Int. J. Hydrogen Energy. 46 (2021) 33756–33781. doi:10.1016/J.IJHYDENE.2021.07.189.

[28] Fab.City, About - Fab.City, (n.d.). https://fab.city/about.html (accessed August 23, 2022).

[29] United Nations, Goal 12 | Department of Economic and Social Affairs, (n.d.). https://sdgs.un.org/goals/goal12 (accessed August 23, 2022).

[30] United Nations, Sustainable consumption and production, (n.d.). https://www.un.org/sustainabledevelopment/sustainable-consumption-production/ (accessed May 26, 2022).

[31] C.J. Turner, R. Ma, J. Chen, J. Oyekan, Human in the loop: Industry 4.0 technologies and scenarios for worker mediation of automated manufacturing, IEEE Access. 9 (2021) 103950–103966. doi:10.1109/ACCESS.2021.3099311.

[32] Ministry of Defence, Department for Business Energy and Industrial Strategy, Air Defence and Offshore Wind Working Together Towards Net Zero, 2021.

[33] H. Trittin-Ulbrich, A.G. Scherer, I. Munro, G. Whelan, Exploring the dark and unexpected sides of digitalization: Toward a critical agenda:, Organ. 28 (2020) 8–25. doi:10.1177/1350508420968184.

[34] The Royal Society, Explainable AI: the basics, 2019.

[35] S. Das, E. Mao, The global energy footprint of information and communication technology electronics in connected Internet-of-Things devices, Sustain. Energy, Grids Networks. 24 (2020) 100408. doi:10.1016/J.SEGAN.2020.100408.

[36] S.J. Qin, Process data analytics in the era of big data, AIChE J. 60 (2014) 3092–3100. doi:10.1002/aic.14523.

[37] Deloitte, The Deloitte Consumer Review Made-to-order: The rise of mass personalisation, 2019. http://www.deloitte.com/view/consumerreview (accessed June 9, 2022).

[38] CISCO, Building Consumer Confidence Through Transparency and Control, 2019. https://www.cisco.com/c/dam/en_us/about/doing_business/trust-center/docs/cisco-cybersecurity-series-2021-cps.pdf (accessed June 9, 2022).

[39] The Royal Society, Digital technology and the planet, 2020.

[40] Michael Chui, James Manyika, Mehdi Miremadi, Nicolaus Henke, Rita Chung, Pieter Nel, Sankalp Malhotra, Sizing the potential value of AI and advanced analytics | McKinsey, 2018. https://www.mckinsey.com/featured-insights/artificial-intelligence/notes-from-the-ai-frontier-applications-and-value-of-deep-learning (accessed June 13, 2022).

[41] E.& I.S. Department for Business, National AI Strategy , 2021. https://www.gov.uk/government/publications/national-ai-strategy (accessed September 29, 2022).

[42] Anshuk Gandhi, Carmen Magar, Roger Roberts, How technology can drive the next wave of mass customisation, 2013. https://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/bto/pdf/mobt32_02-09_masscustom_r4.ashx (accessed June 13, 2022).

[43] P. Webb, S. Asif, A. Tiwari, L. Tinkler, N. Lohse, Reconfigurable robotics for responsive manufacture - R3M, (2021). https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/V051180/1 (accessed June 13, 2022).

[44] Beyond the Barrel: How Data and Analytics will become the new currency in Oil and Gas, (n.d.). https://gblogs.cisco.com/ca/2018/06/07/beyond-the-barrel-how-data-and-analytics-will-become-the-new-currency-in-oil-and-gas/ (accessed June 13, 2022).

[45] 2022 Cyber Security Statistics: The Ultimate List Of Stats, Data & Trends | PurpleSec, (n.d.). https://purplesec.us/resources/cyber-security-statistics/ (accessed June 14, 2022).

[46] Gartner Survey Shows 57% of Manufacturing Leaders Feel Their Organization Lacks Skilled Workers to Support Smart Manufacturing Digitization Plans, (n.d.). https://www.gartner.com/en/newsroom/press-releases/2021-05-11-gartner-survey-shows-57-percent-of-manufacturing-leaders-feel-their-organization-lacks-skilled-workers-to-support-smart-manufacturing-digitization-plans (accessed June 15, 2022).

[47] Sarah Sharples, Future industrial worker, 2018.

[48] I. Collier, P. Shakspeare, Manufacturing The Future Workforce, 2020.

[49] F. Livesey, Public images of manufacturing in the UK: the current situation and future prospects, 2013.

[50] MAKE UK, Why does manufacturing matter to the British public?, 2020.

[51] Paul Wellner, Victor Reyes, Heather Ashton, Chad Moutray, Creating pathways for tomorrow's workforce today, 2022. https://www2.deloitte.com/us/en/insights/industry/manufacturing/manufacturing-industry-diversity.html/#the-growing (accessed June 15, 2022).

[52] MAKE UK, Manufacturing Our Recovery through Inclusion , 2021. https://www.makeuk.org/insights/reports/manufacturing-our-recovery-through-inclusion (accessed June 15, 2022).

[53] N. Tilmes, Disability, fairness, and algorithmic bias in AI recruitment, Ethics Inf. Technol. 2022 242. 24 (2022) 1–13. doi:10.1007/S10676-022-09633-2.

[54] World Economic Forum, The Global Gender Gap Report, 2018.

[55] Guide To Diversity and Inclusion In Manufacturing - Made Smarter, (n.d.). https://www.madesmarter.uk/resources/resource-uk-manufacturing-diversity-inclusion-guide/ (accessed June 15, 2022).

[56] 2020 Global human capital trends report, 2020. https://www2.deloitte.com/cn/en/pages/human-capital/articles/global-human-capital-trends-2020.html (accessed June 15, 2022).

[57] Plan for five careers in a lifetime , Financ. Times. (2017). https://www.ft.com/content/0151d2fe-868a-11e7-8bb1-5ba57d47eff7 (accessed August 23, 2022).

[58] MAKE UK, Digital skills for a digital manufacturing future , 2020. https://www.makeuk.org/insights/reports/digital-skills-for-a-digital-manufacturing-future (accessed June 15, 2022).

[59] World Economic Forum, Recession and Automation Changes Our Future of Work, But There are Jobs Coming, Report Says > Press releases | World Economic Forum, (n.d.). https://www.weforum.org/press/2020/10/recession-and-automation-changes-our-future-of-work-but-there-are-jobs-coming-report-says-52c5162fce/ (accessed June 15, 2022).

[60] The Future of Jobs - Reports - World Economic Forum, (n.d.). https://reports.weforum.org/future-of-jobs-2016/chapter-1-the-future-of-jobs-and-skills/ (accessed June 15, 2022).

[61] Ozkan-Ozen, Yesim Deniz, Y. Kazancoglu, Analysing workforce development challenges in the Industry 4.0, Int. J. Manpow. 43 (2022) 310–333. doi:10.1108/IJM-03-2021-0167/FULL/PDF.

[62] Taking the strain: the last sievewright – in pictures | Art and design | The Guardian, (n.d.). https://www.theguardian.com/artanddesign/gallery/2021/nov/15/taking-the-strain-the-last-sievewright-in-pictures (accessed August 23, 2022).

[63] N.M.P. Bocken, S.W. Short, Unsustainable business models – Recognising and resolving institutionalised social and environmental harm, J. Clean. Prod. 312 (2021) 127828. doi:10.1016/J.JCLEPRO.2021.127828.

[64] Smart Industry Readiness Index - About, (n.d.). https://siri.incit.org/about (accessed June 15, 2022).

[65] Feremy Jurgens, Beh Swan Gin, The Global Smart Industry Readiness Index Initiative: Manufacturing Transformation Insights Report 2022 A R Y 2 0 2 2, 2022.

[66] The keys to a successful digital transformation | McKinsey, (n.d.). https://www.mckinsey.com/business-functions/people-and-organizational-performance/our-insights/unlocking-success-in-digital-transformations (accessed June 15, 2022).

[67] Environmental, Social, and Governance (ESG) Criteria, (2022). https://www.investopedia.com/terms/e/environmental-social-and-governance-esg-criteria.asp (accessed April 26, 2022).

[68] Klaus Schwab, Saadia Zahidi, The Future of Jobs Report 2020, 2020.

[69] Eurofound, Employment impact of digitalisation, (2019). https://www.eurofound.europa.eu/data/digitalisation/research-digests/employment-impact-of-digitalisation (accessed June 16, 2022).

[70] Paul Wellner, B. Dollar, Heather Ashton Manolian, L. Monck, A. Hussain, The future of work in manufacturing, 2019.

[71] IPCC, Climate Change 2022, 2022.

[72] Companies taking action - Science Based Targets, (n.d.). https://sciencebasedtargets.org/companies-taking-action (accessed April 25, 2022).

[73] Climate Data for Action | Climate Watch | Emissions and Policies, (2022). https://www.climatewatchdata.org/ (accessed April 26, 2022).

[74] CDP, Global Supply Chain Report 2020 , 2021. https://cdn.cdp.net/cdp-production/cms/reports/documents/000/005/554/original/CDP_SC_Report_2020.pdf?1614160765 (accessed April 25, 2022).

[75] M. Fischedick, J. Roy, A. Abdel-Aziz, A. Acquaye, J.. Allwood, J.. Ceron, Y. Geng, H. Kheshgi, A. Lanza, D. Perczyk, L. Price, E. Santalla, C. Sheinbaum, K. Tanaka, Industry, in: Clim. Chang. 2014 Mitig. Clim. Chang. Contrib. Work. Gr. III to Fifth Assess. Rep. Intergov. Panel Clim. Chang., Cambridge University Press, Cambridge, UK, 2014.

[76] Why acting now on Net Zero gives organisations an early mover advantage - PwC UK, (2022). https://www.pwc.co.uk/issues/transformation/case-studies-and-insights/net-zero-early-mover-advantage.html (accessed April 26, 2022).

[77] Deloitte., The net zero workforce, 2021.

[78] The Institution of Engineering and Technology, IET skills for net zero and a green recovery 2020 survey, London, UK, 2021.

[79] First Insight, The State of Consumer Spending, 2020.

[80] Deloitte, Sustainability & Consumer Behaviour 2021 | Deloitte UK, (2021). https://www2.deloitte.com/uk/en/pages/consumer-business/articles/sustainable-consumer.html (accessed April 25, 2022).

[81] MAKE UK, Towards a Net-Zero Carbon: UK Manufacturing Sector, London, 2020.

[82] A.J. Lockwood, G. Hill, M. Moldoveanu, R. Coles, R. Scott, Digitalisation of Legacy Machine Tools, Sheffield, UK, 2020.

[83] The Industry and Regulators Committee-House of Lords, Industry and Regulators Committee 1st Report of Session 2021-22 The net zero transformation: delivery, regulation and the consumer, London, UK, 2022. https://committees.parliament.uk/publications/9141/documents/159550/default/ (accessed April 26, 2022).

[84] R. Carmichael, Behaviour change, public engagement and Net Zero: A report for the Committee on Climate Change, London, 2019. http://www.imperial.ac.uk/icept/publications/ (accessed April 26, 2022).

[85] Centre for Sustainabilty and Excellence | Unintended Consequences – the Social Impact of Sustainability Technologies, (n.d.). https://cse-net.org/unintended-consequences-the-social-impact-of-sustainability-technologies/ (accessed June 6, 2022).

[86] UK Critical Minerals Intelligence Centre, (n.d.). https://ukcmic.org/ (accessed August 23, 2022).

[87] What are Critical Raw Materials?, (n.d.). https://www.techbuyer.com/blog/what-are-critical-raw-materials-crm (accessed June 7, 2022).

[88] Yasmina Lembachar, Jordi Pascual, Elisabetta Pennazio, Meritxell Rovira, Circular economy, enabling the transition towards net zero, Glasgow, 2022. https://drive.google.com/file/d/1I2mOQBY2zHMIZN8_xXWEZzYhVJ2ywnlz/view (accessed May 10, 2022).

[89] CE-HUB, What is the Circular Economy? - CE Hub, (n.d.). https://ce-hub.org/ (accessed May 10, 2022).

[90] I.J. Aberkane, From Waste to Kwaste: On the Blue Economy in Terms of Knowledge Flow, Springer Proc. Complex. (2017) 283–290. doi:10.1007/978-3-319-45901-1_31.

[91] Ellen MacArthur Foundation, The power of digital technologies to enable the circular economy, (2021). https://medium.com/circulatenews/the-power-of-digital-technologies-to-enable-the-circular-economy-5471d097ee7f (accessed May 10, 2022).

[92] European Union: European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on Powering a Climate-Neutral Economy: An EU Strategy for Energy System Integration, Brussels, 2020.

[93] How blockchain can enable carbon tracking within the supply chain – Capgemini UK, (n.d.). https://www.capgemini.com/gb-en/article/how-blockchain-can-enable-carbon-tracking-within-the-supply-chain/#_ftn2 (accessed June 7, 2022).

[94] The Royal Society, Climate Change: Science and solutions | Computing for net zero , 2021. https://royalsociety.org/-/ (accessed May 10, 2022).

[95] Bullet-proofing supply chains top priority for manufacturing bosses in 2022 - Digital Catapult | Digital Catapult, (n.d.). https://www.digicatapult.org.uk/news-and-insights/press-releases/post/supply-chains-manufacturing-bosses-in-2022/ (accessed June 17, 2022).

[96] Transforming manufacturing resilience could add £26bn of productivity value to the economy | RS Components, (2021). https://uk.rs-online.com/web/generalDisplay.html?id=footer1/release/210308_resilienceindex_uk (accessed June 30, 2022).

[97] The BCG Henderson Institute, How Resilient Businesses Created Advantage in Adversity During COVID-19 | BCG, (n.d.). https://www.bcg.com/publications/2021/how-resilient-companies-created-advantages-in-adversity-during-covid (accessed June 30, 2022).

[98] McKinsey Global Institute, Could climate become the weak link in your supply chain?, 2020. www.mckinsey.com/mgi. (accessed June 30, 2022).

[99] R. Gurumurthy, R. Nanda, D. Schatsky, Putting digital at the heart of strategy, 2021.

[100] Supply Chain Collaboration | Improve Supply Chain Networks, (n.d.). https://www.valuechain.com/products/network-portal/ (accessed August 24, 2022).

[101] E.& I.S. Department for Business, Modernising consumer markets: Consumer Green Paper, (2018).

[102] Severn Trent creates machine learning to help tackle leakage by filtering five billion data points | News Releases | News | Severn Trent Water, (n.d.). https://www.stwater.co.uk/news/news-releases/severn-trent-creates-machine-learning-to-help-tackle-leakage-by-/ (accessed June 30, 2022).

[103] UU claims world's largest smart leak detection network - Utility Week, (n.d.). https://utilityweek.co.uk/uu-claims-worlds-largest-smart-leak-detection-network/ (accessed June 30, 2022).

[104] Proposal for legislation to improve the UK's cyber resilience - GOV.UK, (n.d.). https://www.gov.uk/government/consultations/proposal-for-legislation-to-improve-the-uks-cyber-resilience (accessed June 30, 2022).

[105] European Union: European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability, 2020.

[106] Geological Survey of Sweden, Critical raw materials, (n.d.). https://www.sgu.se/en/mineral-resources/critical-raw-materials/ (accessed June 30, 2022).

[107] Temperatures | Climate Action Tracker, (n.d.). https://climateactiontracker.org/global/temperatures/ (accessed June 30, 2022).

[108] N. Agarwal, N. Seth, Analysis of supply chain resilience barriers in Indian automotive company using total interpretive structural modelling, J. Adv. Manag. Res. 18 (2021) 758–781. doi:10.1108/JAMR-08-2020-0190/FULL/XML.

[109] Grant funding success rates: chances of success in 2022 - RedKnight Consultancy | Grant Bid Writers | Funding Bid Writers | Bid Writers, (n.d.). https://redknightconsultancy.co.uk/2022/02/23/grant-funding-success-rates/?utm_source=rss&utm_medium=rss&utm_campaign=grant-funding-success-rates (accessed August 24, 2022).

[110] World Economic Forum, International Finance Corporation, Financing Resilience in Post-COVID-19 Manufacturing and Supply Systems, (2021).

[111] Annual Manufacturing Report, 2020. https://www.pwc.co.uk/industries/manufacturing/insights/annual-manufacturing-report.html (accessed June 30, 2022).

[112] Employee Well-Being Report, Industry Spotlight | Glint, (n.d.). https://www.glintinc.com/blog/employee-well-being-report-industry-spotlight-retail-and-manufacturing/ (accessed June 30, 2022).

[113] Welcome to Reshoring UK, (n.d.). https://www.reshoring.uk/ (accessed August 24, 2022).

[114] Deloitte., Impact of Brexit on the manufacturing industry: Managing through uncertainty, 2017.

[115] United Nations Environment Programme, GRID-Arendal, Spreading like Wildfire: The Rising Threat of Extraordinary Landscape Fires | UNEP - UN Environment Programme, 2022. https://www.unep.org/resources/report/spreading-wildfire-rising-threat-extraordinary-landscape-fires (accessed August 24, 2022).

[116] Fire Services deal with "unprecedented" number of incidents during the heatwave, (n.d.). https://www.nationalfirechiefs.org.uk/News/fire-services-deal-with-unprecedented-number-of-incidents-during-the-heatwave (accessed August 24, 2022).

[117] The Nippon Telegraph and Telephone Corporation, 2021 Global Threat Intelligence Report, 2021.

[118] J. Hughes, Ż. Muranko, D. Parker, A. Ramjee, R. Waugh, M. Moss, E. Mckenna, S. Thompson, B. Peace, S. Yarwood, P. Huggett, Y. Wang, A study of the Potential of VRPs for Resource Efficiency, 2022.

[119] The Periodic Table of Endangered Elements - American Chemical Society, (n.d.). https://www-acs-org.nottingham.idm.oclc.org/content/acs/en/greenchemistry/research-innovation/endangered-elements.html (accessed July 1, 2022).

[120] Hannah Bloomfield, What Europe's exceptionally low winds mean for the future energy grid, Conversat. (2021). https://theconversation.com/what-europes-exceptionally-low-winds-mean-for-the-future-energy-grid-170135 (accessed August 24, 2022).

[121] Michael Gasiorek, Supply chain resilience: The dangers of "pick n mix," 2022. https://ec.europa.eu/info/strategy/priorities-2019-2024/ (accessed July 1, 2022).

[122] Davide Furceri, Swarnali A Hannan, Jonathan David Ostry, Andrew K. Rose, Macroeconomic consequences of tariffs, 2019. https://www.imf.org/en/Publications/WP/Issues/2019/01/15/Macroeconomic-Consequences-of-Tariffs-46469 (accessed July 1, 2022).

[123] R. Bradley, M. Alderman, Forget fail fast: How a customized and adaptive strategy can drive your digital supply network, 2018.

[124] O. Fisher, N. Watson, L. Porcu, D. Bacon, M. Rigley, R.L. Gomes, Cloud manufacturing as a sustainable process manufacturing route, J. Manuf. Syst. 47 (2018). doi:10.1016/j.jmsy.2018.03.005.

[125] Mckinsey Digital, Smartening up with Artificial Intelligence (AI) , 2017.

[126] H.J. Wilson, P.R. Daugherty, Collaborative Intelligence: Humans and AI Are Joining Forces, Havard Bus. Rev. (2018).

[127] Sharebox - Secure sharing, (n.d.). sharebox-project.eu/#overview (accessed July 10, 2019).

[128] O.J. Fisher, N.J. Watson, J.E. Escrig, R.L. Gomes, Intelligent Resource Use to Deliver Waste Valorisation and Process Resilience in Manufacturing Environments, Johnson Matthey Technol. Rev. 64 (2020) 93–99. doi:10.1595/205651320X15735483214878.

[129] Jin Xuan, Biomanufacturing with carbon capture and utilisation: A Zero Carbon Loss System, (2022). https://gtr.ukri.org/projects?ref=EP%2FW018969%2F1 (accessed July 1, 2022).

Faculty of Engineering
University of Nottingham
University Park
Nottingham
NG7 7RD