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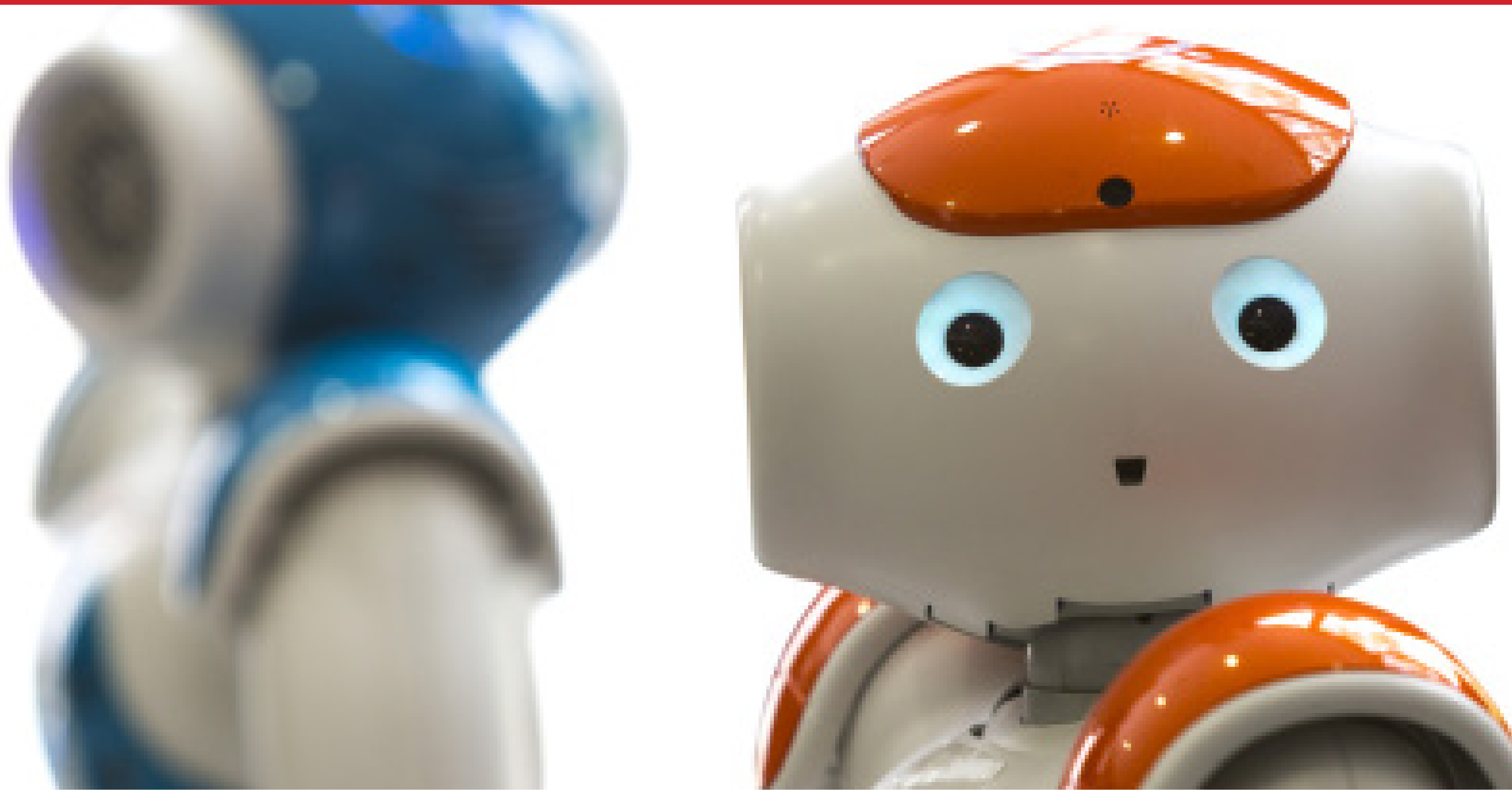

Emerging trends in global advanced manufacturing:

CHALLENGES, OPPORTUNITIES AND POLICY RESPONSES

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

EMERGING TRENDS IN GLOBAL ADVANCED MANUFACTURING:

CHALLENGES, OPPORTUNITIES AND POLICY RESPONSES

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PREFACE

In 2013, the University of Cambridge's Institute for Manufacturing, in collaboration with the United Nations Industrial Development Organization (UNIDO) published the report Emerging Trends in Global Manufacturing Industries. The report was part of a UNIDO series that is intended to present different, and possibly diverging, assessments of the megatrends that shape the future of manufacturing.

The 2013 report analysed major emerging technologies with the potential to transform manufacturing as we know it, such as nanotechnology, synthetic biology and 3D printing. This new study provides an update on that report, accounting for recent developments and adding particular emphasis on policy implementation. It reviews the following themes: (a) megatrends driving change in advanced manufacturing, (b) science and technological developments receiving increasing policy attention, (c) emerging challenges and opportunities for value capture, and (d) recent advanced manufacturing policy programmes and initiatives in selected countries.

The themes and examples discussed in the report present a range of scenarios, not necessarily exhaustive, to inform policies, programmes and practises to support manufacturing-based innovation and economic growth.

This report is based on a review of recent national policies, foresight exercises and research strategies from selected major manufacturing economies and has also been informed by discussions with manufacturing innovation experts from around the world.

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Executive summary

Governments around the world are increasingly putting emphasis on the interplay between manufacturing, innovation and economic growth. The 20th century model where technological innovation was driven by a small number of countries with a handful of research universities and dominant R&D-intensive corporations is rapidly changing. In this new global context, being able to rapidly scale-up emerging technologies into commercial manufacturing applications, and successfully coordinate the complex manufacturing systems into which these technologies diffuse, may become the critical factors for capturing high value from advanced manufacturing-based industries.

However, policy making in the area of advanced manufacturing is becoming increasingly challenging. Manufacturing keeps evolving as a result of a changing global societal, economic and technological landscape. Megatrends such as globalisation, climate change and a growing middle-class underlie the fundamental manufacturing challenge to *produce more with less*. At the same time, manufacturing systems are becoming increasingly complex, cutting across sectors and technologies. Advances in science and engineering present new opportunities for manufacturers around the world. Across industries and countries, it is still uncertain who the winners (and losers) will be.

Building on a previous collaboration with UNIDO, this report provides an update on the megatrends and technological developments driving change in global advanced manufacturing, paying particular attention to the increasing digitalisation of manufacturing.

Case studies illustrating how advanced manufacturing is being supported by government policy programmes are drawn from major manufacturing countries including USA, UK, Japan and Germany. These examples reveal that opportunities and challenges to capturing value in advanced manufacturing can be found not only in the development of more sophisticated products, but also in the engineering of better production technologies and systems, the establishment of more efficient and responsive supply chains, and through a better understanding of customer needs.

The report also identifies a broad international recognition that effective policies require a systemic understanding of innovation. In particular, it is increasingly recognised that R&D funding, while a basic component in an innovation policy portfolio, is in itself not sufficient to achieve industrial competitiveness and economic growth. Policies are also required across complementary innovation functions to support the scale-up of emerging technologies, commercialisation of those technologies by business, technology adoption by small and medium-sized enterprises (SMEs) and the development of new advanced manufacturing skills.

A number of approaches and insights that might support advanced manufacturing policy making are highlighted in this report. The first is the adoption of new sources of data and analytical approaches – beyond national statistics based on traditional industrial classifications – to better understand challenges and opportunities in advanced manufacturing, and the potential role of policies to support it. In this context, the potential contribution of policy units, research institutes and think tanks in providing insights into challenges and opportunities across industries and technologies is emphasised. Similarly, the report emphasises the potential of policies, programmes and institutions to facilitate close interaction and sharing of insights between laboratory-based researchers, manufacturing engineers, equipment manufacturers and user industries to support the industrialisation of emerging technologies.

The report argues that interpreting manufacturing as a cross-cutting theme can help reveal the linkages between science, technology and innovation (STI) policies, and industrial strategies. As part of policy analyses, asking common manufacturing questions across industries and technologies can provide insights into strategic issues (including cross-sectoral challenges and opportunities), which cannot be fully revealed by analysing individual technologies or particular industry sectors independently.

Finally, the report discusses the growing importance of policies in supporting the supply of more sophisticated and multidisciplinary manufacturing skills while addressing demographic change. It is emphasised that, contrary to a perception held in some segments of society, advanced manufacturing-based industries provide some of the newest and most exciting career opportunities.

The themes and examples discussed in this report provide an international context to inform policies, programmes and practices to support advanced manufacturing-based innovation and economic growth.

1 | Introduction

The importance of advanced manufacturing is being increasingly recognised by policy-makers around the world. The contribution of manufacturing to national economies *today* is emphasised in national policy documents in terms of delivering well-paid jobs, attracting foreign direct investment (FDI), increasing productivity and improving other economic variables. More recently, however, the importance of manufacturing to national economies *tomorrow* is receiving growing attention due to its role as the main driver of business R&D expenditure and as a key enabler of the industrialisation of emerging technologies.

> *"...the importance of manufacturing to national economies* **tomorrow** *is receiving growing attention due to its role as the main driver of business R&D expenditure and as a key enabler of the industrialisation of emerging technologies."*

As industries become more complex and the pace of technological change increases, designing policies to support advanced manufacturing is becoming increasingly challenging.

Megatrends are reshaping the way in which manufacturing firms operate and conduct their business. Changing consumer preferences are redefining the types of manufacturing products and services demanded globally. The sources of value capture within industries are shifting and traditional patterns of industrial leadership are being challenged.

Furthermore, new technologies offer the potential to create new markets based on entirely new products and services. In particular, the digitalisation of manufacturing, has emerged as one of the most important themes in national innovation policy agendas (and R&D portfolios) of major economies. Increasing attention is being paid to a range of digital technologies and concepts such as the internet-of-things, big data and cloud computing, but also to advanced robotics, artificial intelligence, visualisation technologies and 3D printing.

In this changing context, it is still unclear who the winners (and losers) across industries and nations will be, and the role that policy-makers can play in supporting industrial innovation.

The scope for policy-makers to foster innovation in manufacturing is potentially broad and often uncertain. It is increasingly recognised that the challenges are not only limited to funding basic and applied R&D. They also extend to supporting the scale-up of disruptive/emerging technologies, promoting commercialisation by business and adoption by SMEs, while fostering balanced regional development.

This report provides an update to the 2013 UNIDO-IfM report *Emerging Trends in Global Manufacturing Industries*. It is based on a review of national and regional research strategy documents, academic studies, research agency reports and other selected studies emerging from selected important manufacturing economies – in particular the USA, Germany, the UK, Japan and the European Union.

The main intended audience of this report are practitioners working in government, in particular: industry/economic departments; national innovation agencies; manufacturing research and innovation institutes; and anyone interested in major developments (in particular technology developments) affecting global manufacturing industries.

> ***"It is increasingly recognised that the challenges for policy-makers are not limited to funding basic and applied R&D. They also extend to supporting the scale-up of disruptive/emerging technologies, promoting commercialisation by business and adoption by SMEs, while fostering balanced regional development."***

This report aims to:

- Review major trends and drivers shaping the future of advanced manufacturing and discuss policy implications
- Discuss practical implementation mechanisms in major manufacturing economies
- Stimulate debate about national policies, programmes and practices to support manufacturing-based innovation and economic growth

The remainder of this report is structured as follows:

- **Section 2** presents a review of megatrends driving change in global advanced manufacturing
- **Section 3** discusses recent science and technology developments, with particular emphasis on the 'digitalisation' of manufacturing and technology 'scale-up'
- **Section 4** discusses value capture in advanced manufacturing, and suggests how policy could structure the analysis of challenges and opportunities
- **Section 5** presents case studies of advanced manufacturing initiatives and programmes to provide an international context and illustrate differences in international approaches
- **Section 6** provides concluding remarks and discusses policy implications

2 | Megatrends driving change in global advanced manufacturing

OVERVIEW OF THIS SECTION

This section reflects upon recent social, economic and technological developments around the world to provide an updated view of the megatrends shaping the future of advanced manufacturing reviewed in the 2013 report *Emerging Trends in Global Manufacturing Industries*. Some of the trends discussed in the previous report remain relevant and, as such, this updated review does not discuss them in detail.

The list of megatrends analysed in this section includes:

- **Continuing ageing of the workforce in developed countries:** Population ageing in some world regions is expected to challenge lifestyles and consumption patterns as well as to diminish the size of the available workforce for manufacturing
- **Changing manufacturing skills needs:** The technological evolution of manufacturing is transforming the skills requirements of its workforce. This, in combination with population ageing, is already leading to a shortage of qualified manufacturing labour
- **Growing demand for customised products:** Adaptability to increased demand for customised products and services according to consumers' individual specifications is becoming critical to market and value capture for companies around the world
- **Increasing demand for manufactured goods in cities:** The need for urban infrastructure to address a growing demand for urban mobility, energy, housing and telecommunication solutions is becoming a prominent driver of new manufacturing requirements
- **Growing interest in industrial and technological strategies:** Governments across both emerging and high-wage economies are embarking on the design of detailed industrial and technology strategy programmes to maximise the economic benefits of manufacturing
- **Increased efforts to support reshoring to developed countries:** Reshoring of manufacturing activities has gained increased policy attention as a potential strategy to expand the domestic manufacturing base and foster high-wage job creation, innovation and exports

2.1 | Introduction

Megatrends are major (non-sector-specific) global trends shaping the future of manufacturing with the potential to redefine sources of industrial competitiveness. With their pervasive effects on global industry, megatrends drive what needs to be produced, where and how. The 2013 report *Emerging Trends in Global Manufacturing Industries* identified eight megatrends affecting the manufacturing sector at the global level (see Box 1). Since then, several other studies have discussed new emerging global trends that could have an impact on the future of manufacturing

> ***"Megatrends are major (non-sector-specific) global trends shaping the future of manufacturing with the potential to redefine sources of industrial competitiveness. They drive competing agendas as to what needs to be produced, where and how."***

in the context of the so-called Fourth Industrial Revolution[1].

This section reflects upon these new studies to provide an update of megatrends shaping the future of advanced manufacturing.

Both megatrends and technological developments are relevant to manufacturing. For example, the digitalisation of manufacturing activities and demographic trends interact to shape the future of manufacturing. The digitalisation of production processes is transforming work within factories and driving new skill requirements. While digitalisation might address a shortage of workers due to an ageing population, there is also concern that it might drive a further loss of productive employment. Thinking about the future of manufacturing therefore requires a holistic perspective.

While some of the megatrends examined in this section were discussed to some extent in the 2013 report, their importance has been further emphasised since then. Similarly, some of the trends discussed in the previous report remain relevant and, as such, this updated review does not discuss them in detail. The megatrends discussed in this section are the following: continuing ageing of the workforce; changing manufacturing skills needs; rowing demand for customised products; increasing demand for manufactured goods in cities; growing interest in industrial and innovation policies; increased efforts to support reshoring to developed countries.

BOX 1. 'MEGATRENDS' REVIEWED IN THE 2013 REPORT *EMERGING TRENDS IN GLOBAL MANUFACTURING INDUSTRIES*

The 'megatrends' discussed in the 2013 report included the following:

- **Globalisation** (offshoring and outsourcing; rising manufacturing powers)
- **Sustainability** (resource- and energy-efficient manufacturing; carbon footprint; quality of life and consumption)
- **Demographics** (growing global middle-class; ageing manufacturing workforce; 'bottom-of-the-pyramid' markets)
- **Urbanisation** (mobility, housing and infrastructure needs; urban factories)
- **Threats to global stability** (natural disasters; terrorism threats)
- **Accelerating production life cycles** (increasing rates of technological innovation; increasing technological pervasiveness, novel manufacturing processes)
- **Changing consumer habits** (individualism; faster technological adoption)
- **National industrial policies** (increasing policy efforts to support manufacturing-based economic growth)

Source: López-Gómez, C., O'Sullivan, E., Gregory, M., Fleury, A., and Gomes, L. (2013). *Emerging Trends in Global Manufacturing Industries*. United Nations Industrial Development Organization.

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[1] This 'Fourth Industrial Revolution' follows the first industrial revolution in which production was mechanised through the use of steam power, the second industrial revolution in which mass production was developed through the use of electric power, and the third digital revolution in which computers and ICT were used to enhance the automation of manufacturing.

2.2 | Continuing ageing of the workforce

The world population is expected to reach 8.5 billion by 2030 and 9.7 billion by 2050 (UN, 2015), with Africa and Asia accounting for most of this growth. These two regions are expected to represent almost 80% of the world's population by 2050, up from 76% in 2015 (UN, 2015). Meanwhile, a number of nations, particularly in Europe, are expected to experience a decrease in population. Due to low fertility rates, countries such as Bulgaria, Croatia, Hungary and Romania are expected to see their populations decline by more than 15% by 2050 (UN, 2015).

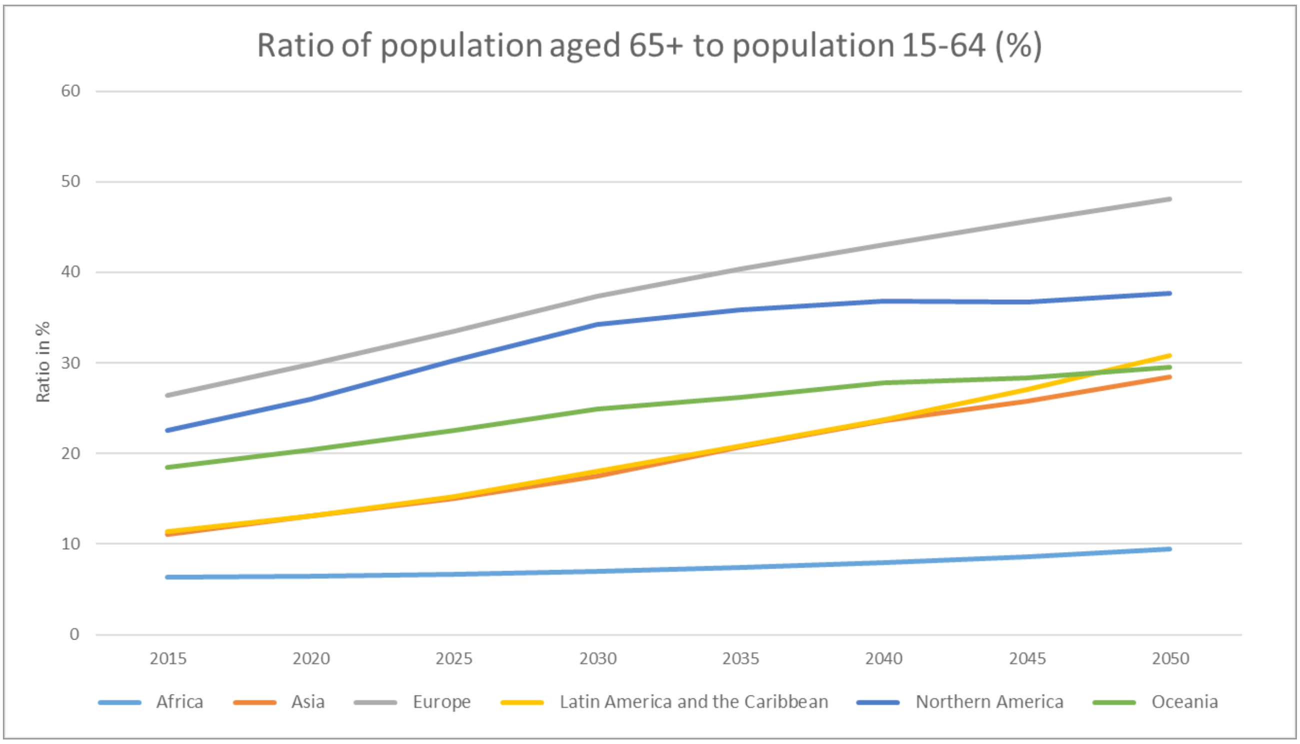
"Population ageing is expected to have an impact on the share of workers over the number of retirees. This could not only represent a challenge for the sustainability of healthcare and social protection systems, but also for skilled workforce availability in the manufacturing sector."

A demographic change in the world population will also occur. Today, young populations dominate some of the fastest growing world regions. In Africa, for example, children under 15 years old represented 41% of the population in 2015 and young people aged 15 to 24 made-up an additional 19%. In Asia and Latin America there was a smaller percentage of children compared to Africa (24-26%), but similar percentages of youth (16-17%). In contrast, Europe had the highest percentage of its population aged 60 or over (24%) in 2015. Meanwhile 49% of Japan's population was aged over 60 in 2015, and this is expected to rise to 59% by 2030. Overall declining fertility rates and increasing life expectancy across the world are likely to generate substantial ageing of the world population. If these trends continue, it is anticipated that by 2050 all the world regions, with the exception of Africa, would have a quarter or more of their population aged 60 or over.

Population ageing is expected to have an impact on the ratio of workers to retirees. This ratio is expected to decline in several countries, implying that the size of the dependent population (i.e. non-working population aged under 15 and over 65) as a share of the working population will increase to a level where the sustainability of healthcare and old-age social protection systems could be challenged (Figure 1).

Population ageing is also expected to impact on lifestyles and consumption patterns, with implications for the manufacturing sector in regard to the types of products and services demanded (DASTI, 2016). Furthermore, following the reduction in size of the working-age population, companies might struggle to find workers with the right skills. Therefore, investments in several industries is expected to be guided by the availability of the right knowledge and skills (Teknikföretagen, 2013).

Figure 1. Old-age dependency ratio



Source: elaborated with data from UN (2015).

2.3 | Changing manufacturing skills needs

The technological changes shaping the future of advanced manufacturing are expected to transform the type of skills required by its workforce. Traditional manufacturing processes based on division of labour could be embedded in new integrated organisational structures, where coordination will be required to manage interactions between real and virtual machines, plant control systems and production systems (ACATECH, 2013).

In particular, technology is changing both the type of workers needed (i.e. from general to specialised labour) and the type of skills that are required (CMC, 2016). Advanced manufacturing requires workers with new multidisciplinary competencies, combining mechanics, electronics and software knowledge and skills. New roles in information management are emerging across the value chain and proficiency in new computerised modelling and simulation tools and data analytics is increasingly required. Complex systems thinking and cyber-security competencies are becoming more important as processes and machines become increasingly interdependent. Proficiency in methodologies for real-time decision making are also more important, as it is the knowledge of international standards. More generally, some of the most radical innovations emerging today will only deliver their full benefits to society when technicians, engineers and managers are able to embed them into new products, processes and manufacturing systems operating at full industrial scale. In addition, manufacturing jobs will demand workers be equipped with hybrid abilities involving deep technical specialisation coupled with business awareness (Foresight, 2013).

“The technological changes shaping the future of advanced manufacturing are transforming the type of skills required by its workforce. This, in conjunction with an ageing workforce, is already leading to observable labour shortages in most industrialised countries.”

An ageing workforce coupled with higher skills requirements may lead to a shortage of high skilled workers in some industries. Although the impact is expected to vary between manufacturing sectors and countries, several reports show that labour shortages are already being experienced in industrialised countries around the world. In the USA for example, a 2015 survey (Deloitte, 2015) found that there will be 3.5 million new manufacturing jobs created over the next decade. However, it is anticipated that nearly 57% of those jobs could remain unfilled due to the skills gap between the job requirements and the actual skills of the American workforce. The survey estimated there was already a substantial skills gap in USA manufacturing with 600,000 unfilled jobs in 2011. Similarly, skills and labour shortages are considered the most important issues for manufacturing in Canada, where the existing skills gap is expected to increase in the next five years (CMC, 2016). In the UK, it is estimated that 35% of the vacancies in the manufacturing sector are hard to fill, mainly because of a lack of technical skills among the applicants, as well as a lack of relevant experience (EEF, 2016). In Australia, the number of graduates in STEM disciplines is below the OECD average. Furthermore, around 45% of workers in the Australian domestic manufacturing sector do not hold any post-school qualification, compared to 39% for all industries (CISRO, 2016).

Governments and the business sector are working together to address the skills shortage of manufacturing’s highly specialised workforce, as highlighted in most of the policy reports reviewed for this report. However, it remains unclear whether this type of cooperation would be enough to close the skills gap driven by the increasing demand for highly skilled workers in the manufacturing sector. In the USA for example, the Federal Government has supported apprenticeship programmes, funded community colleges, and disbursed tax credits and loans targeted to companies hiring skilled workers (Deloitte, 2015). In Ireland, the Smart Future programme is aimed at promoting STEM careers among secondary school students. By 2020 the Irish Government, in partnership with industry, is also expected to launch new apprenticeship and traineeship programmes targeting the most innovative sectors (Ireland, 2015). Similar cross-sectoral programmes are already being implemented in the UK (AMSG, 2016).

2.4 | Growing demand for customised products

As discussed in the 2013 report, the projected growth of the global middle-class, mainly in Asia and other emerging economies, is driving new consumer markets and increasing demand for customised products and services to meet the growing demand for individualisation (López-Gómez et al, 2013).

Global consumers have also developed a stronger desire to tell manufacturers what appeals to them and as a result manufacturers have created customised products according to each customer’s own individual specifications (Gupta et al, 2011). Customisation of products and services is, therefore, likely to become increasingly critical to capture value (Conroy et al, 2015).

"Adaptability to increased demand for customised products and services according to consumers' individual specifications is becoming critical to market and value capture for companies around the world."

This presents a double challenge to manufacturers. Firstly, companies need to spend time and resources understanding differences in consumer preferences and values in distinct regions of the world to provide products that better meet customers' specific needs (Gupta et al, 2011). Secondly, companies need to develop new business models and flexible manufacturing systems capable of producing relatively small batches of customised products at competitive costs that mimic mass production prices. Achieving profitable mass customisation of products and services is a demanding task because it increases manufacturing complexity.

Some examples of customisation are shown in Table 1 for different industries (adapted from Gandhi et al, 2013).

Table 1. Product customisation examples for different industries

Industry	Customisation example	Technological trends
Apparel	Sports shoes with the option of choosing different colours for different elements	Suits/shirts fit to body measurements or scans
Food	Frozen yogurt with custom topping choices	Personalised food and vitamins based on nutritional needs
Consumer electronics	Laptop with choice of colour, size of hard drive, and keyboard language	Individualised colours and graphics
Automotive	Vehicle with choice of colours, seats, accessories, and so on	Individualised colours, artwork, and body shapes
Health care	Drug combinations customised for the patient	DNA-based personalised medicine
Entertainment and connectivity services	Choice of pre-defined entertainment services menu	Artificial Intelligence enabled delivery of personalised services and products

Source: adapted from Gandhi et al (2013).

To address this mass customisation challenge, the following capabilities are expected to become important for manufacturing firms:

- Capability to develop affordable customised products – deliver a much wider range of product specifications in shorter time frames at an affordable price
- Customisation capability for local and global markets – local regulations and market needs will drive the demand for locality-specific product characteristics, while developing countries will acquire the technological knowledge to compete at the global level

In summary, firms will need to further develop their innovation and technological capabilities to cope with increasing demand and competition. As discussed later in this report, emerging technologies enabling the digitalisation of manufacturing will support manufacturing industries to respond to greater demands for personalisation. It is therefore, not surprising that the technologies that can deliver individualised products and services, such as 3D printing, are often highlighted as critical elements in policy documents from different countries.

2.5 | Increasing demand for manufactured goods for cities

People living in urban areas exceeded the global rural population for the first time in history in 2007 (UN, 2014). In 2014, 54% of the world population (3.9 billion) lived in urban areas and this share is expected to increase to 66% by 2050 (Figure 2). Nearly 90% of this increase will be concentrated in Asia and Africa, with three countries – China, India and Nigeria – accounting for 37% of such growth.

Urbanisation trends are likely to lead to a substantial increase in demand for manufacturing products and services across the construction and urban infrastructure value chains, namely the transport, energy, and telecommunications markets (PwC, 2015). Urban populations have already been the main source of domestic demand in emerging economies (e.g. China) for both spending on new infrastructure and consumption of goods by the middle-class (DASTI, 2016).

> *“Urbanisation growth could lead to a substantial increase in demand for manufacturing products and services for mobility, housing, energy, communications and environmental solutions.”*

Between 2015 and 2030, it is anticipated that three-quarters of global consumption growth will be generated by just 600 cities, with nearly one-quarter of total consumption growth generated by only 32 cities (McKinsey Institute, 2016). As previously discussed, manufacturing firms will need to understand consumption needs across distinct regions and countries, including the growing demand for individualisation, to be able to reach this growing urban market and remain competitive.

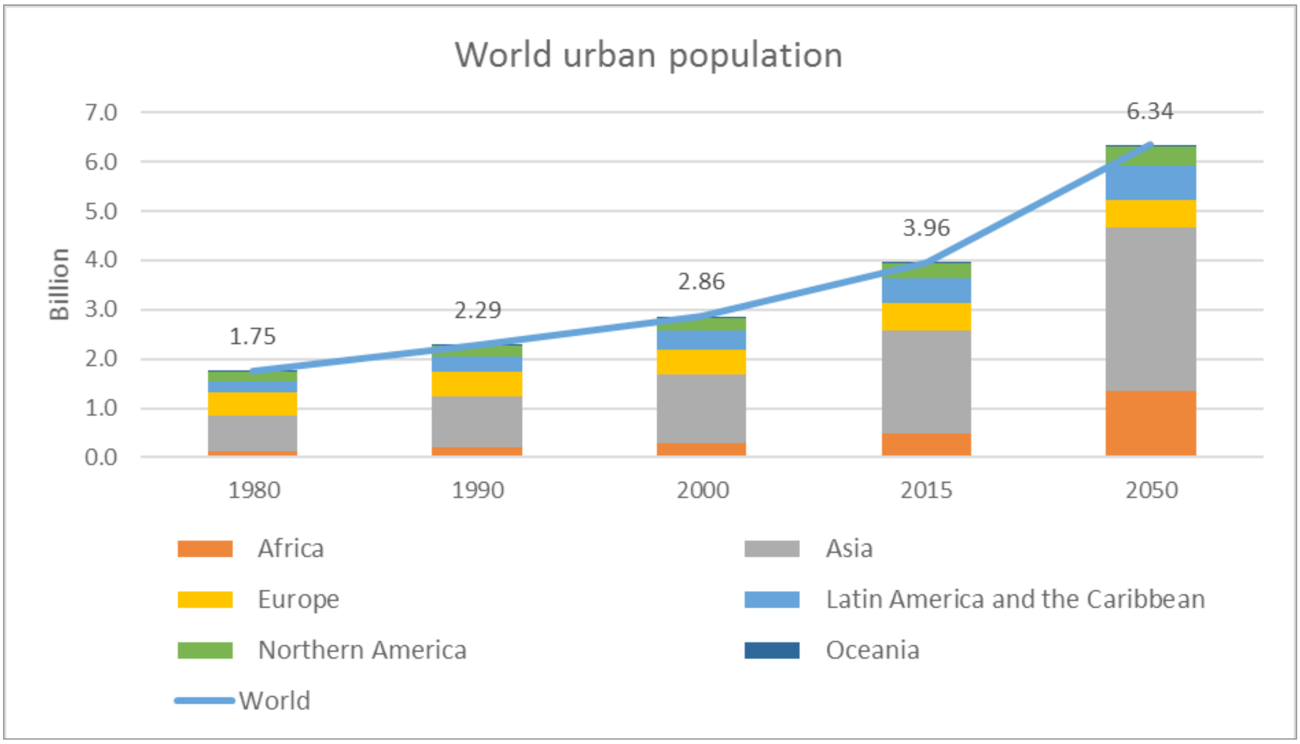
As the pace of urbanisation increases it is likely that demand for products and services to meet the needs of urban populations will grow too. For this purpose, manufacturing products and services will be required to provide solutions in the following categories:

- Mobility solutions, challenged by problems such as ageing infrastructure and expanding suburbs

- Housing solutions and the ability to build affordable houses for the poorest sectors of the urban population
- Environmental solutions for cities, particularly in relation to water quality, air pollution, and waste disposal

In industrialised countries, where the level of urbanisation is already higher, there is increasing interest in the development of 'Smart Cities', which are designed for sustainable growth and enhancing the well-being of their populations. Smart Cities use information and communication technologies (ICT) to deliver mobility, housing and environmental solutions. Smart Cities require the innovative and evolving integration of existing smart technologies and governance models (European Commission, 2014). For manufacturing, this represents an opportunity to shape the future of cities by delivering new products and services underpinned by the same digital technologies involved in the so-called Fourth Industrial Revolution.

Figure 2. World urban population projection to 2050



Source: elaborated with data from UN (2014).

2.6 | Growing interest in industrial and technological strategies

In recent years, a new emphasis has been put on the role of industrial strategies as a tool to manage the economic changes associated with the shift of wealth to emerging regions and the reshaping of global value chains, especially since China emerged as a global manufacturing power. Many developing countries have implemented industrial strategies to diversify and upgrade their industrial structures. Tailored policies and tools have also been developed to foster scientific and technological innovation at the national level. Furthermore, the creation of new firms, particularly technology start-ups, has also been considered as a policy goal (OECD, 2013; ILO, 2014).

China's national industrial and technology plan Made in China 2025 integrates advances in ICT across 10 key technological domains. This plan represents the first step of a 30-year three-step strategy. Its implementation will be suported by additional policies aimed at bringing appropriate institutional reform and financial backing. The plan includes measures to eliminate out-dated manufacturing activities and promote greater energy efficiency, environmental protection and resource utilisation.

> *"Industrial and technological strategies are increasingly seen as valuable tools to foster scientific and technological capabilities for competitiveness in high-value manufacturing activities in the context of growing global competition."*

A renewed interest in industrial and innovation strategies has also emerged among industrialised countries that already possess diversified and mature industrial structures. In these cases, industrial strategies are aimed at strengthening the competitive advantage of the economy by fostering science and technology innovation, in close cooperation with industries. Examples include countries such as the UK, Germany, Japan and the USA.

In 2013, the UK Government launched a series of industrial strategy papers to define the long-term investment strategies of some economic sectors in order to secure jobs and economic growth. The core characteristic of those strategies is that they are based on a strategic partnership between the Government and industry with a focus on sectoral promotion through technology and skills development, access to finance and procurement (HM Government, 2014). Building upon this experience, in 2017 the UK Government released a green paper titled 'Building our Industrial Strategy'. This paper sets up the foundation to build a 'modern industrial policy' for the UK, with the objective of improving living standards and economic growth (see Box 2). This strategy, the UK Government argues, is not about economic planning or 'picking winners' but rather about identifying the competitive strengths of the economy and defining ways in which the Government can help industries to become more competitive in the long-term.

BOX 2. THE UK'S GREEN PAPER 'BUILDING OUR INDUSTRIAL STRATEGY'

In 2017 the UK Government published a green paper outlining its new approach to industrial strategy. The paper establishes 10 industrial pillars to support competitiveness of the UK economy:

- Investing in science, research and innovation
- Developing skills
- Upgrading infrastructure
- Supporting business to start and grow
- Improving procurement
- Encouraging trade and inward investment
- Delivering affordable energy and clean growth
- Cultivating world-leading sectors
- Driving growth across the whole country
- Creating the right institutions

Source: HM Government (2017).

BOX 3. GERMANY'S 'NEW HIGH-TECH STRATEGY'

The German innovation strategy is based on the following measures:

- Using the potential of key technologies (for example, digital technologies integrated with production processes) for the benefit of industry
- Strengthening innovative SMEs
- Increasing the numbers of innovative start-ups
- Enhancing the innovation resources of structurally weak regions

Source: BMBF (2014a).

German industrial programmes have recently focused on fostering innovation within industries as outlined in 'The New High-Tech Strategy' (see Box 3), which identifies priorities in key area of research and innovation. The German Government recognises that even companies with highly innovative products could face difficult market conditions, such as access to finance, to fully exploit the returns of their innovations. In this respect, public funding can help companies to overcome such market challenges and, eventually, to create more jobs and growth.

In Japan, the Cross-Ministerial 'Strategic Innovation Promotion Programme' (SIP) was launched in 2015 as a science, technology and innovation strategy aimed at addressing the most important problems faced by Japan and contributing to economic growth (see Box 4).

BOX 4. JAPAN'S 'STRATEGIC INNOVATION PROMOTION PROGRAMME' (SIP)

The programme identifies 10 key themes in energy, next-generation infrastructure and regional resources where public investments will be directed:

- Innovative combustion technology
- Next-generation power electronics
- Structural materials for innovation, aimed at accelerating the development of innovative lightweight, heat- and environment-resistant materials for Japan's aviation industry
- Energy carriers (i.e. renewable energy sources)
- Next-generation technology for ocean resources exploration
- Self-driving cars, including next-generation urban transport, to create a safe road traffic environment
- Infrastructure maintenance, renovation and management
- Enhancement of societal resiliency against natural disasters
- Technologies for creating next-generation agriculture, forestry and fisheries
- Innovative design/manufacturing technologies, focused on creating regional innovation by developing new technologies to respond to consumer and business' needs.

Source: CSTI (2015a).

In the USA, the Obama administration launched the 'Strategy for American Innovation' (see Box 5), which recognised the key role of the Government in science and innovation investment and the promotion of technology innovation in the industrial sector. This strategy was based on the assumption that fostering innovation can lead to improved job quality and sustained economic growth.

BOX 5. USA'S 'STRATEGY FOR AMERICAN INNOVATION'

Strategic areas of intervention under this initiative include:

- Investing in building blocks for innovation, including investment in fundamental research and high quality STEM education
- Empowering American innovators by, for example, establishing prize incentives
- Creating quality jobs and lasting economic growth by investing in emerging technologies and advanced manufacturing

Source: NEC and OSTP (2015).

2.7 | Increased efforts to support reshoring to developed countries

Manufacturing reshoring, defined as "the company decision to relocate activities back to the home country regardless of the ownership of the activities relocated" (Stentoft et al, 2016, p 3), has gained increased policy attention in recent years in a number of countries.

At the firm level, six main drivers have been identified behind the push for reshoring (Stentoft et al, 2016):

- Cost reduction
- Quality improvement
- Time and flexibility
- Access to skills and knowledge
- Risk reduction
- Market access

Among these factors, cost is considered to be the main driver behind the decision to reshore. The major cost deciding factors are increasing costs for labour, logistics and energy, as well as productivity differences between locations (Stentoft et al, 2016).

A 2014 survey of UK companies found that one in seven companies have undertaken reshoring activities since 2009. The survey also showed that reshoring companies decided to switch to UK-based suppliers rather than maintaining suppliers from low-cost countries (EEF, 2014).

Similarly, the 2010-2012 European Manufacturing Survey of more than 3,000 European manufacturing firms found that for every three offshoring firms (i.e. companies relocating business processes away from their home country) there was one reshoring firm (Dachs and Zancher, 2014).

In terms of policy attention, reshoring is growing in prominence as part of the political agenda in a number of countries. In the USA for example, the US Economic Development Administration commissioned a study in 2015 for the International Economic Development Council to "examine current reshoring practices and create materials to spread awareness of reshoring trends, tools and resources that are available to ease the process" (Nash-Hoff, 2016). In the same way, reshoring has been frequently included in many official documents of EU institutions (De Backer et al, 2016). For instance, the Communication of the European Commission For a European Industrial Renaissance includes explicit references to reshoring and, in general, considers reshoring among the key policy goals in the new European-level industrial policy.

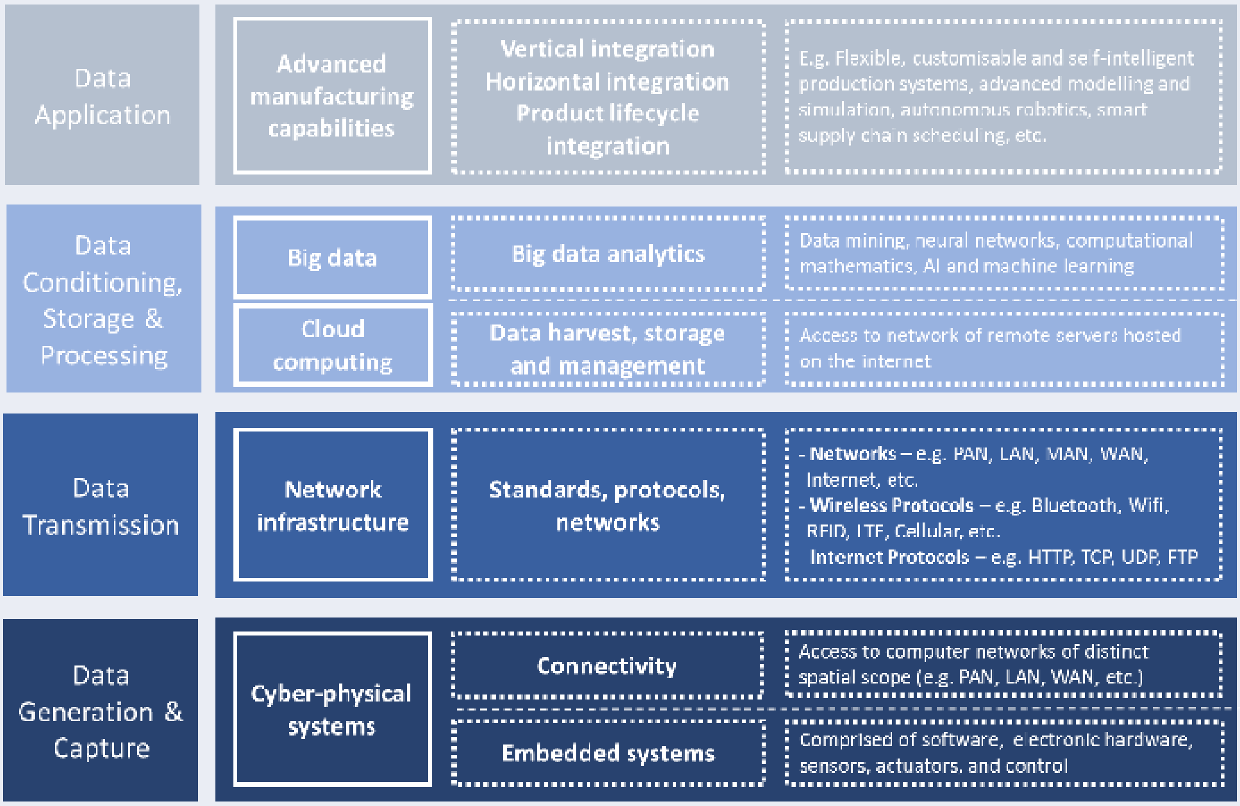
> *"Reshoring of manufacturing activities has gained increased policy attention as a potential strategy to expand the domestic manufacturing base and foster high-wage job creation, innovation and exports."*

Despite the increasing interest, managing the expectations about the impact of reshoring and the reindustrialisation of advanced economies is not a straightforward task (De Backer et al, 2016). The fact that some companies are reshoring some manufacturing activities does not imply the end of offshoring. In this respect, empirical evidence shows companies can decide to bring back some activities to serve home markets more effectively, but at the same time they can relocate other activities to foreign markets (De Backer et al, 2016). Although employment gains are associated with reshoring activities, it is not expected that employment in the manufacturing sector will return to the level it was 30 years ago. This is because technological progress and productivity improvements have reduced the number of manufacturing jobs. In conclusion, the mixed evidence about the impact of reshoring should not prevent policy-makers considering it as a potential policy goal. Taking into account the above discussion, any policy goals involving reshoring activities should be realistically set to manage expectations.

3 | Digitalisation, scale-up and value capture: technological trends of growng importance

OVERVIEW OF THIS SECTION

- This section discusses science and engineering domains that have gained increased policy attention since the publication of the 2013 report *Emerging Trends in Global Manufacturing Industries* (Box 1).
- The section pays particular attention to the digitalisation of manufacturing and the scale-up of novel technologies.
- While the list of technologies discussed here is not comprehensive, a schematic overview of the most significant technology families that converge to generate the so-called 'digitalisation of manufacturing' is presented.
- Six technological domains are discussed in detail: internet-of-things, cyber-physical systems, big data, cloud computing, artificial intelligence and machine learning.
- In terms of novel technology scale-up challenges, this section discusses a number technology tools of increasing importance for facilitating and enabling successful innovation scale-up in manufacturing, including advanced metrology and sophisticated modelling and simulation tools.



3.1 | Introduction

This section provides insights into science and engineering developments expected to gain relevance in future industrial systems. Two key developments are receiving particular attention in the international policy agenda: the digitalisation of manufacturing and efforts to scale-up emerging technologies.

The list of technologies discussed here builds on the technology areas reviewed in the 2013 report *Emerging Trends in Global Manufacturing Industries* (Box 1), which remain relevant. The objective of this section is not to revisit those technologies, but to discuss new science and engineering domains that have gained importance around the world since the publication of the previous report, as they are likely to play an increasingly prominent role in enabling the production-related concepts and transformations described later in this report.

The list of scientific and technological developments presented here is not comprehensive.The review focuses mainly on technology areas with the potential to increase manufacturing capabilities in a broad range of manufacturing industries, enabling the next wave of high-value products and production technologies. A detailed technical discussion of these technologies is beyond the scope of this report. However, the descriptions presented here provide insights into the expected nature of the change they can drive in future manufacturing systems.

This section begins by presenting the technology areas reviewed in the previous edition of this report in Box 6, followed by an in-depth discussion on digitalisation and scale-up.

BOX 6. EMERGING SCIENCE AND ENGINEERING DEVELOPMENTS FROM THE 2013 REPORT *EMERGING TRENDS IN GLOBAL MANUFACTURING INDUSTRIES*

The following technology areas were emphasised:

- Photonics: Scanning, sensing and imaging; information, communication and networks; screens and displays; advanced lighting; photonic energy systems; and laser systems
- Biotechnology: Biopharma; tissue engineering/regenerative medicine; synthetic biology; and bio-inspired manufacturing using self-assembly
- Nanotechnology: Carbon nanotubes; nanocomposite structural materials; nanoelectronics; nanotechnology-based coatings; nanoparticles; and nano-tagging
- Additive manufacturing: Automated fabrication; solid free-form fabrication; direct digital manufacturing; stereolithography; three-dimensional or 3D printing; and rapid prototyping
- Microtechnology: Micro-tooling (for replication) manufacturing and micro-systems in machine tools and products
- ICT in manufacturing systems: Intelligent mechatronic systems for automation and robotics (e.g. self-adapting components) and advancement of grid computing for manufacturing
- Advanced materials: Advanced composites and metamaterials
- Environmental and energy technologies: Resource recovery and reuse; renewable feedstocks; electricity storage; fuel cells; renewable energy (solar, wind, geothermal, bioenergy and hydro); nuclear fission and fusion; and advanced vehicles

Source: López-Gómez, C., O'Sullivan, E., Gregory, M., Fleury, A., and Gomes, L. (2013). *Emerging Trends in Global Manufacturing Industries*. United Nations Industrial Development Organization.

3.2 | The digitalisation of manufacturing

In recent years, the digitalisation of manufacturing has emerged as one of the most important themes in the manufacturing and innovation policies (and R&D portfolios) of major economies. In particular, the convergence of digital technologies such as cyber-physical systems, cloud computing, big data, artificial intelligence, machine learning and the internet-of-things, among others, offers the potential to more effectively connect and integrate manufacturing systems. These families of technologies (and associated enabling technologies) offer the promise of enabling more rapid development of new products and more efficient logistics, as well as allowing manufacturing industries to respond to customer and user demands such as greater personalisation, higher safety, and improved energy and resource efficiency.

3.2.1 | Trends, drivers and semantics of the digitalisation of manufacturing

The international advanced manufacturing policy documents reviewed for this study highlighted the common trends and drivers for the digitalisation of manufacturing, including:

- **Customer demand trends:** When explaining the potential of digitalisation, policy documents often highlight customer demand for the following: product variety; personalised products and services; faster response to needs; expectations of added-value services (social media interaction, order status tracking); and societal and economic pressure to increase environmental and resource sustainability
- **User industry pressures and drivers:** Some policy documents also highlight the following industry challenges: increasing need for asset and resource efficiency; growing reliance on supply chain and need for robustness and tracking; increasing security risks; shorter product lifecycles; emerging opportunities to offer value-added services throughout product lifecycle; and increasing manufacturing complexity of products, production and data
- **Technology trends**: The digitalisation of manufacturing is underpinned by a range of different emerging technologies and systems that support the enhanced organisation, sharing and analysis of data; improved sensing and interacting with the material world; and greater connectivity, data gathering, and control of manufacturing system elements

From a policy perspective[2], this increased interest in digitalisation is driven by a range of factors, including:

- The potential to enhance productivity and economic growth
- The implications (both opportunities and challenges) for manufacturing jobs in high wage economies as discussed in the previous sections
- Concerns about a disconnect between manufacturing and innovation (with implications for ongoing competitiveness in key technology domains)
- Concerns about cyber-security of industrial systems and utilities
- Cost and supply constraints
- Sustainability of natural resources (and the potential for the digitalisation of manufacturing to enhance resource efficiency)
- The potential for new markets based on entirely new products or services

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[2] See among others MEI (2016), ACATECH (2016), and CSIRO (2016)

> ***"When comparing international research and innovation policies for the digitalisation of manufacturing, it should also be noted that different countries use a range of similar and related terms: smart manufacturing, digital manufacturing, industrial internet, smart factories, cloud manufacturing, Fourth Industrial Revolution, cyber-physical production systems, etc."***

When comparing international research and innovation policies for the digitalisation of manufacturing, it should also be noted that different countries use a range of similar and related terms: smart manufacturing, industrial internet, smart factories, cloud manufacturing, Fourth Industrial Revolution, cyber-physical production systems, etc. These terms do not necessarily have a one-to-one correlation and are not necessarily defined or used consistently.

However, a number of terms have come to be used as shorthand for the collection of converging trends (and future opportunities) related to the digitalisation of manufacturing:

- Industry 4.0: This term originates from a strategic initiative of the German Government's New High-Tech Strategy (Industrie 4.0). The term refers to an anticipated Fourth Industrial Revolution where cyber-physical systems, cloud computing, big data, artificial intelligence, machine learning and the internet-of-things will more effectively connect and integrate manufacturing systems. The term is now widely used in many countries and by many international firms, management consultancies and the media. The term is typically used to cover all efforts to integrate and connect vertically, horizontally and along product lifecycles (as defined above), by contrast with terms such as smart factories, smart manufacturing and digital manufacturing which often have narrower definitions.
- Smart manufacturing versus digital manufacturing: In the USA the term 'digital manufacturing' (often associated with the traditional computer aided design (CAD) community) refers to the use of digital representations of objects and their subsequent manufacture. Digital manufacturing in this definition focuses on the use of integrated systems involving simulation, 3D visualisation, as well as various analysis and collaboration tools. The term 'digital thread' is often associated with digital manufacturing referring to the data associated with activities along the (design-to-manufacturing) product lifecycle. 'Smart manufacturing', by contrast, often refers to the integration and networking of manufacturing system elements within a factory, enterprise and supply chain, using model-based decision-making to optimise processes, logistics and supply chain management, and reduce downtime of machines, 'Smart manufacturing' as defined above has been more widely deployed in chemical and process industries. Digital manufacturing approaches have been more widely deployed in discrete product and assembly industries.

> ***"The term 'Industry 4.0' originates from a strategic initiative of the German Government and refers to an anticipated Fourth Industrial Revolution where cyber-physical systems, cloud computing, big data, artificial intelligence, machine learning and the internet-of-things will more effectively connect and integrate manufacturing systems."***

3.2.2 | Value capture from the digitalisation of manufacturing

At least four main sources of value capture opportunities originate from the Fourth Industrial Revolution based on the digitalisation of manufacturing:

- Adoption of Industry 4.0 systems: There is potential for user industries adopting Industry 4.0 to capture value from greater efficiency, flexibility, speed/responsiveness, precision and customisation
- Manufacturing of key technology elements for Industry 4.0: There is significant potential for some firms to make significant revenues from key technology elements (embedded systems, robots, etc.)
- Knowledge management and analysis: Some firms will capture value from selling tools or services enabled via the internet-of-things
- Building the infrastructure: Some firms will capture significant value from growing markets providing the sensors, batteries, broadband infrastructure, and other technologies that underpin the expanding internet-of-things

BOX 7. EXAMPLES OF NATIONAL RESEARCH AND DEVELOPMENT PRIORITIES AROUND THE DIGITALISATION OF MANUFACTURING

National research and development priorities around the digitalisation of manufacturing reflect local historical scientific and industrial structures and/or strengths, as well as the interests of dominant manufacturing industries within the economy. Examples of national variations in terms of emphasis include:

- The US emphasis is on cloud computing and artificial intelligence (e.g. Google) to obtain value from accumulated data through the use of big data analytical techniques
- Japan's aim is to lead in the development of robots in the internet-of-things era by developing global standards for common robot infrastructure in manufacturing and strengthening artificial intelligence technology applied to robotics
- Germany's major goal is to lead the standardisation for connecting production machines under Industry 4.0 efforts

Source: O'Sullivan, E. (2016). A Review of International Policy Approaches to Supporting Research & Innovation for the Digitalisation of Manufacturing. Institute for Manufacturing, Centre for Science, Technology & Innovation Policy.

3.2.3 | Science & technological developments underpinning the digitalisation of manufacturing

The digitalisation of manufacturing is supported by the development of a wide range of different technologies and systems that allow improved sensing and interacting with the material world, the enhanced organisation, sharing and analysis of data, and much greater connectivity, data gathering, and control of manufacturing system elements. The convergence of digital technologies such as the internet-of-things, cyber-physical systems, big data, cloud computing, artificial intelligence and machine learning enables the development of advanced manufacturing capabilities for Industry 4.0. These include flexible, customisable and self-intelligent production systems, advanced modelling and simulation, autonomous robotics, and smart supply chain scheduling, among others.

The rest of this section discusses these technologies in further detail by first introducing a framework to understand how all of these digital technologies interact with one another under the encompassing boundaries of the internet-of-things (Figure 3), which incorporates all other digital technologies mentioned here. This framework works as a visual map to understand the interrelation of these digital technologies and their role in enabling the advanced manufacturing capabilities of Industry 4.0.

Internet-of-Things

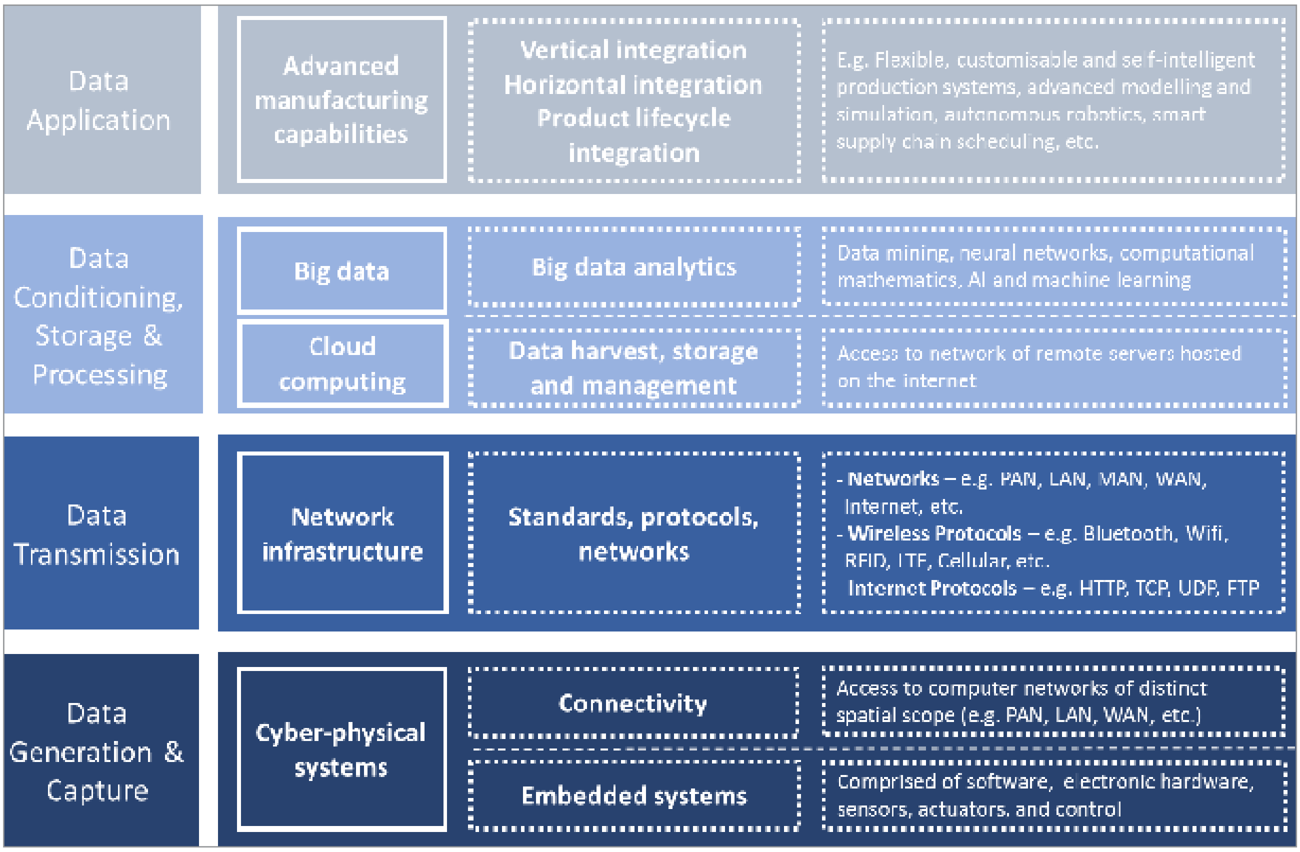
The internet-of-things refers to networks of physical objects (devices, vehicles, buildings, equipment, etc.) containing electronic hardware, software and sensors, that enable them to be connected to the internet. This allows objects to collect and exchange data. The internet-of-things is facilitated by the convergence of a wide range of digital technologies – particularly cyber-physical systems, wireless networks, cloud computing, big data, artificial intelligence and machine learning – and is expected to find important applications in industry and other sectors such as consumer and home services, energy, transport systems, health care, entertainment and public services (OECD, 2015).

"The internet-of-things refers to networks of physical objects (devices, vehicles, buildings, equipment, etc.) containing electronic hardware, software, and sensors to enable them to be connected to the internet. This allows objects to collect and exchange data."

The use of internet-of-things technologies in manufacturing is commonly known as the industrial-internet-of-things (IIoT). In addition to the digital technologies mentioned above, the industrial internet-of-things incorporates communication and automation technologies that have existed in industrial settings for many years. A simplified framework for understanding the relationship between all the digital technologies involved in supporting the internet-of-things is shown in Figure 3, with a particular focus on its role as an enabler of advanced manufacturing capabilities.

In the internet-of-things, cyber-physical systems generate and capture data from the physical world and transmit it through the network infrastructure for it to be analysed and employed by distinct applications. During this process, the network must have the capacity to transmit and analyse large volumes of data (big data), and applications that can make use of cloud computing with the necessary processing power to deal with these substantial amounts of information. This data can be used to feed machine learning algorithms that increase the artificial intelligence of smart manufacturing machines and systems that learn and communicate in real time, allowing them to make their own decisions and therefore adapt and optimise their operations even in changing conditions. Similarly, this data can enable companies to detect and address problems sooner, saving time and costs associated with production disruptions. (Vermesan and Friess, 2014).

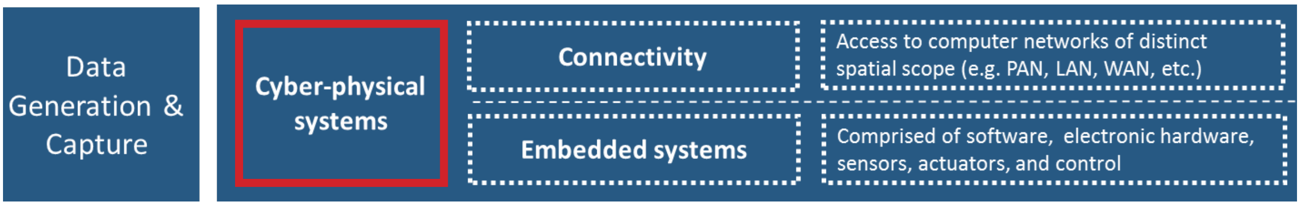
Figure 3. Internet-of-things simplified framework – An advanced manufacturing perspective



Source: Leal-Ayala and O’Sullivan (2017).

In manufacturing, the applications enabled by the internet-of-things range from vertical to horizontal and product lifecycle integration, including flexible, customisable and self-intelligent production systems, advanced modelling and simulation tools, autonomous robotics, smart supply chain scheduling and tracing, quality control and optimisation, and overall supply chain efficiency. Further definitions and insights about the technologies encompassed by the internet-of-things are included in the following sections (Vermesan and Friess, 2014).

Cyber-physical systems



The term ‘cyber-physical systems’ refers to smart networked embedded systems formed of electronic hardware, software, sensors, actuators and control algorithms, designed to sense and interact with the physical world (including human users), and support real-time, guaranteed performance in applications. Current embedded systems are the central control units at work in most modern technological products and devices. They typically operate as information-processing systems to perform device-specific applications (GTAI, 2014). However, their capacity to connect to the online world is currently limited. By adding the ability to transmit the data that they collect with each other and the online world, embedded systems will transform into cyber-physical systems in the future.

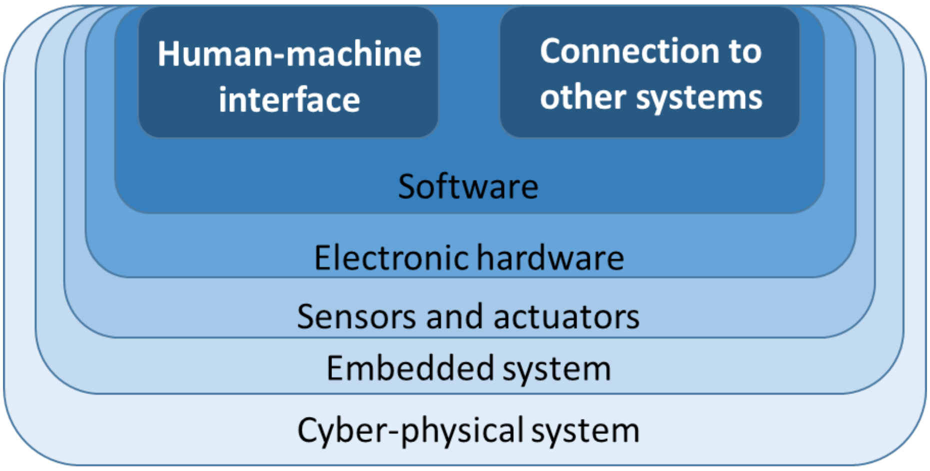
The use of cyber-physical systems in manufacturing is a key fundamental of Industry 4.0 and smart factories. By providing a rich variety of real-time data from production processes, cyber-physical systems will deliver real-time quality, time, resource and cost advantages over classic production systems (GTAI, 2014). The wealth of data collected by these systems will be employed for critical decision-making related to the adaptability, flexibility and customisation of manufacturing operations through the internet-of-things applications outlined earlier in this section.

> ***"The term 'cyber-physical systems' refers to smart networked embedded systems formed of electronic hardware, software, sensors, actuators and control algorithms, designed to sense and interact with the physical world (including human users), and support real-time, guaranteed performance in applications."***

In particular, sensing devices[4] within cyber-physical systems enable a number of advanced manufacturing capabilities such as improved quality control, model validation and improvement, and better quantification of process variability and uncertainty (NSF, 2015a). It is anticipated that future sensing devices within cyber-physical systems will incorporate real-time process analysis, wireless connectivity and be integrated with new technologies to autonomously evaluate sensor health, quantify measurement uncertainty and support efficient calibration procedures (NSF, 2015a).

However, for this to happen, improvements are required in the functionality, performance and cost of these sensors. Similarly, sensor size needs to be reduced to enable the future miniaturisation of cyber-physical systems. Power consumption is a specific area of concern given the aspiration of operating sensors in power-constrained environments.

Figure 4. Key elements of cyber-physical systems



Source: adapted from Brettel et al (2014).

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[4] Example types of sensors include gyroscopes and accelerometers, thermocouples, strain gauges, cameras, humidity sensors and those for chemical and biological species.

> *“The use of cyber-physical systems in manufacturing is a key fundamental of Industry 4.0 and smart factories. By providing a rich variety of real-time data from production processes, cyber-physical systems will enable real-time quality, time, resource and cost advantages in comparison with classic production systems.”*

As a result, power efficiency and local energy harvest are key areas of research and development (NSF, 2015b). The same need exists for other components involved in cyber-physical systems such as batteries, ultracapacitors, energy harvesters, wireless antennae, passive electrical components, switches, optical components, and motors, among others (NSF, 2015b).

Actuators are also a key element for the deployment of cyber-physical systems. In particular, smart actuators will be important for complex part manipulation or assembly and to enable increased speed, precision, quality and higher levels of modularity and performance in dynamic processes (European Commission, 2013).

Wireless networks that allow connectivity and data exchange between cyber-physical systems and between these and the outside world represent another critical requirement for the large-scale deployment of this technology. Common hardware and software systems available to create wireless sensor networks include (Bi et al, 2014):

- **IPv6:** Allows the connection of an unlimited number of devices
- **WiFi and Wimax:** Provide high-speed and low cost communication
- **Zigbee, Bluetooth and RFID:** Provide local and low-speed communication
- **Mobile Platforms:** Offer communications for anytime, anywhere and anything

Ongoing research in this area focuses on energy efficient routing, aggregation, and data management algorithms, as well as the large-scale deployment, integration and security of high data volumes. Similarly, the development of open interfaces, protocols and standards are critical to ensure universal connectivity and interoperability between cyber-physical systems and allow the integration of smart applications throughout the entire enterprise, from machine to process, process to plant, and plant to supply chain (NSF, 2015a).

Big data

The large-scale industrial deployment of cyber-physical systems implanted with sensors, together with improvements in industrial networking, will result in the growth of data volume and traffic, something that is commonly referred to as big data. This term refers to datasets where the size is beyond the capability of typical database software tools to capture, store, manage, and analyse (Tian and Zhao, 2015). Big data has four defining characteristics: volume, velocity, variety and value (Box 8).

BOX 8. CHARACTERISTICS OF BIG DATA

Big data has four defining characteristics:

- Volume: Refers to the large amount of data involved with big data, with scales growing from gigabytes (GB) to terabytes (TB), petabytes (PB) and even exabytes (EB) and zettabytes (ZB).
- Velocity: Data generation speed continues to increase. This results in higher velocity requirements for data processing and analysis due to the real-time nature of data creation and decision-making in support of business processes. As a result, processing capacity must change from batch processing to stream processing.
- Variety: Data types generated in the past were simpler and most of the data was structured. big data is more complex and heterogeneous, existing in many formats, including text, document, image, and video, among others. These complex types of data often include semi-structured or unstructured datasets, adding to its complexity.
- Value: The real value of big data is in the insights it produces when analysed. By extracting important information and knowledge that can be used to transform models for research, production, operations, and sales within enterprises, big data demonstrates its increasing commercial value.

Source: Tian and Zhao (2015).

Despite its value and opportunities, the development of big data also brings technological challenges. In particular, traditional information technology infrastructure and methods for data management and analysis are not ready for the rapid growth of big data. Existing information technology networks present important bottlenecks in terms of their poor scalability, poor fault tolerance, low performance, and difficulty in installation, deployment, and maintenance, among other issues (Tian and Zhao, 2015; European Commission, 2013; NSF, 2015b). New developments in information technologies are required to deal with the real-time demand of big data, particularly in five main categories (Tian and Zhao, 2015):

- Infrastructure support: big data processing requires cloud data centres with large-scale resources as well as cloud computing platforms with efficient resource scheduling and management solutions that are secure, high-performance, reliable and scalable.
- Data acquisition: Data acquisition is an essential pre-step for data processing. This involves not only technologies for collecting data, but also for cleaning, filtering, checking and converting valid data into suitable formats and types.
- Data storage: Due to the large amounts of data involved, distributed file storage systems and distributed databases are required to store the data in multiple (distributed) storage sites.

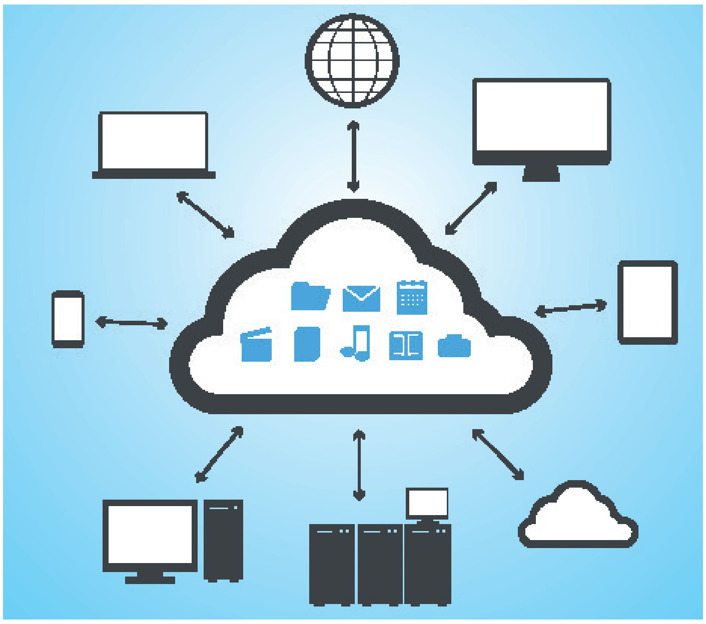
> ***"The large-scale industrial deployment of cyber-physical systems embedded with sensors, together with improvements in industrial networking, will result in the growth of data volume and traffic, something that is commonly referred to as big data. This term refers to datasets where the size is beyond the capability of typical database software tools to capture, store, manage and analyse."***

- Data computing and analytics: Analytical tools will also have to evolve in order to extract the information embedded within big data through fast structuring, analysis and processing of distributed and heterogeneous data sources in near-real time (European Commission, 2013). Big data analytics include sophisticated quantitative methods such as data mining, neural networks, computational mathematics, artificial intelligence and machine learning to discover interrelationships and patterns in the data.
- Display and interaction: In order to fully exploit its value, appropriate visual display formats are essential to achieve a better understanding of big data by industrial users in support of decision making activities within business processes.

Cloud Computing

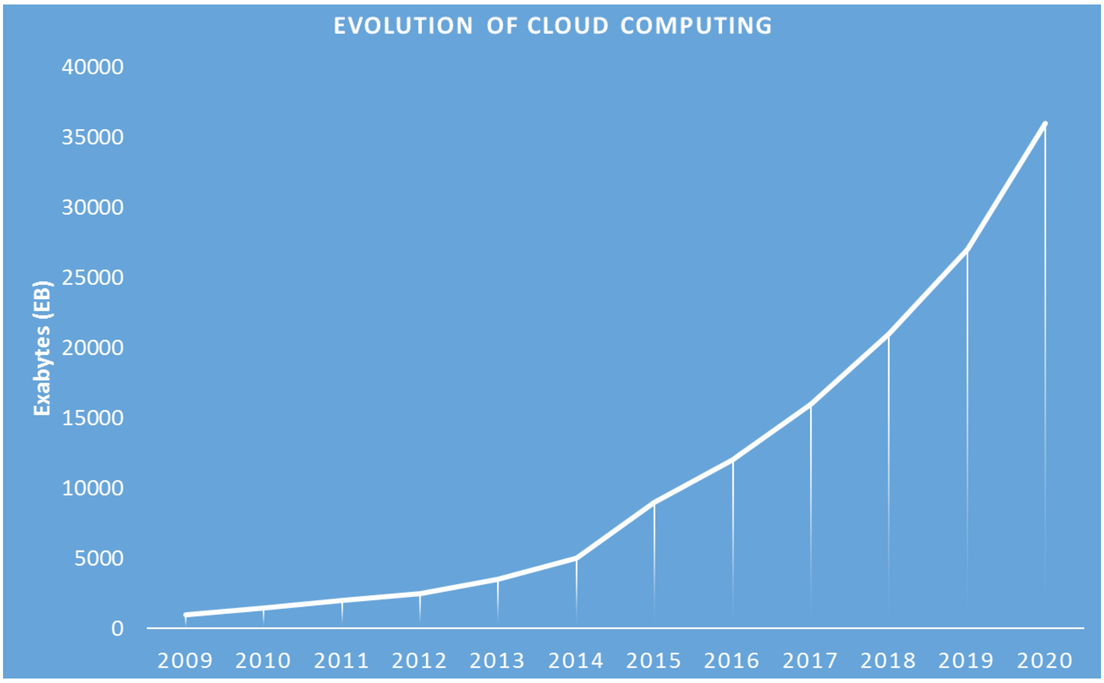
Cloud computing can be defined as the practise of using a network of remote servers hosted on the internet to store, manage, and process data, rather than a local server or personal computer. It's a type of internet-based computing that enables ubiquitous, on-demand access to a shared pool of configurable computing resources (e.g. computer networks, servers, storage, applications and services) that can be quickly provided and released with minimal management effort (Mell and Grance, 2011).

Figure 5. Cloud computing provides ubiquitous, on-demand access to a shared pool of configurable computer resources



Cloud computing and big data are complementary, the former providing a cost-effective way to support the technological infrastructure required to process the large volumes and varied formats of big data. Cloud computing has developed as a response to the massive information processing requirements of the internet age, as a result of both technological trends and social needs (Tian and Zhao, 2015).

Figure 6. Evolution of cloud computing in exabytes (EB)



Source: elaborated with data from Tian and Zhao (2015).

Some of its key characteristics include (Mell and Grance, 2011; Tian and Zhao, 2015):

- **On-demand self-service**: Users can unilaterally request computing capabilities from the cloud as needed, without any human interaction with the service provider, in a way similar to accessing public utilities
- **Broad network access**: Capabilities are available over the network and accessed through standard platforms (e.g., mobile phones, tablets, laptops, and workstations). All cloud services are hosted beyond client boundaries and delivered over the internet
- **Resource pooling**: Cloud resources (e.g. storage, processing, memory and network bandwidth) are pooled to serve multiple consumers, with resources dynamically assigned and reassigned according to consumer demand
- **Rapid elasticity**: Cloud capabilities can be elastically provisioned and released in a way that, to the consumer, the capabilities often appear to be unlimited and can be appropriated in any quantity at any time
- **Measured service**: Resource usage can be automatically monitored, controlled, optimised and reported, providing transparency for both the provider and the consumer

"Cloud computing can be defined as the practise of using a network of remote servers hosted on the internet to store, manage and process data, rather than a local server or personal computer. It enables ubiquitous, on-demand access to a shared pool of configurable computing resources that can be quickly provided and released with minimal management effort."

Based on the relationship between cloud computing providers and users, its commercial deployment model can be classified in four ways:

- **Public Cloud**: Cloud environment for open use by the general public, provided by independent third-party suppliers. It exists on the premises of the cloud suppliers
- **Private Cloud**: Cloud infrastructure built and used exclusively by a single enterprise. Ownership, management and operation may be by the enterprise or a third-party. Cloud users are members of the enterprise only
- **Hybrid Cloud**: Any combination of public and private cloud models

Further widespread adoption of cloud computing presents some risks that need to be addressed in the future. In particular, the following challenges are worth highlighting (Mell and Grance, 2011; Tian and Zhao, 2015):

- **Data Security**: Sensitive information is vulnerable to security breaches and therefore current research activities are highly focused on the development of security solutions. In addition, laws related to secrecy of information are still in development in most places around the world
- **Reliability**: Information should always be available on-demand. This means that having reliable and high-speed network connections is essential to the successful use of cloud computing. Any glitch in the overall system performance could disrupt normal enterprise operations, leading to potential financial losses
- **Management Issues**: The efficient monitoring, scheduling and deployment of cloud resources represents a complex management challenge. Further research and development is required in advanced dynamic resource scheduling algorithms for improved resource sharing efficiency, energy savings and operating cost reduction
- **Standardisation**: Due to its recent development, standards for technology implementation and service delivery have just begun to be homogenised. Open standards are required to ensure the full interoperability in terms of data and applications.

"Cloud computing and big data are complementary, the former providing a cost-effective way to support the technological infrastructure required to process the large volumes and varied formats of big data."

Although cloud computing is not new in manufacturing, the projected digitalisation of manufacturing will require increased data sharing across machines and processes. More machine data will be deployed to the cloud in order to enable more data-driven services for production systems, including cloud-based monitoring and control processes (USDE, 2015). Cloud users will be able to use cloud services according to their requirements, ranging from product design, manufacturing, testing, management, and all other stages of a product life cycle (USDE, 2015).

Artificial Intelligence and Machine Learning

Artificial intelligence refers to intelligence exhibited by machines or, in other words, computer systems able to perform some tasks that are normally considered to require human knowledge, intelligence, learning and understanding, such as visual perception, speech recognition, and decision-making (Russell and Norvig, 2009). How can an artificial intelligence system exhibit some aspects of human intelligence? Machine learning, defined as the ability for an artificially intelligent system to learn without being explicitly programmed (Samuel, 1959), provides the answer to that question. In its most basic form, machine learning refers to the use of algorithms to analyse data, learn from it, and then make decisions about specific tasks. Rather than writing a specific set of software code to instruct a machine to do a particular job, machine learning algorithms give it the ability to learn how to perform a task by training the system using large amounts of data or big data (Copeland, 2016). Therefore, machine learning is an enabler of artificial intelligence.

There are two main types of learning algorithms employed in machine learning: unsupervised and supervised. The former works by asking the learning algorithm to identify structures or clusters of data in unlabelled datasets (i.e. with no right or wrong answers). On the contrary, supervised learning methods use labelled datasets to train a specific model. After a certain number of iterations, the model will eventually be ready to classify new sets of data by itself (Walport, 2015). For many applications, it can be far easier to train a system by showing it many examples of desired input-output behaviour (supervised) than to program it manually to anticipate the desired response for all possible inputs (Jordan and Mitchell, 2015).

"Artificial intelligence refers to intelligence exhibited by machines or, in other words, computer systems able to perform some tasks that are normally considered to require human knowledge, intelligence, learning and understanding, such as visual perception, speech recognition, and decision-making."

Advances in machine learning have been mostly driven by the development of new learning algorithms as well as the availability of big data and low-cost computer power (Jordan and Mitchell, 2015). New smart applications capable of learning from previous situations have opened up a range of uses in health care, manufacturing, education, financial modelling and marketing, among other fields (Jordan and Mitchell, 2015).

The increased availability of data in the manufacturing industry has already resulted in machine learning being successfully employed in applications related to process optimisation, monitoring and control. In addition, machine learning has also been effectively used in predictive maintenance and quality control optimisation processes (Wuest et al, 2016). However, current machine learning applications in manufacturing remain limited to specific processes and do not cover full manufacturing systems (Wuest et al, 2016). Other potential manufacturing applications include warranty reserve estimation, telematics and demand forecasting (The Royal Society, 2015).

A number of practical implementation barriers exist for the widespread adoption of machine learning in manufacturing:

> *"Machine learning refers to the ability of a machine to use algorithms to analyse data, learn from it, and then make decisions about specific tasks. Hence, rather than writing a specific set of software code to instruct a machine to do a particular job, Machine learning algorithms give it the ability to learn about how to perform a task by training the system using large amounts of data or big data."*

- **Complexity and variety**: Machine learning is a diverse field with numerous approaches, theories and methods. The complexity involved in understanding this variety represents a barrier for many manufacturing practitioners (Wuest et al, 2016)
- **Lack of expertise and technological competence:** Staff with the relevant experience in applying machine learning techniques to manufacturing problems are in short supply. Similarly, there is a lack of technological competence in using big data for machine learning algorithms (The Royal Society, 2015)
- **Data quality and availability**: Commonly used industrial devices such as programmable logic controllers (PLC) may not necessarily capture the right type of data for machine learning (The Royal Society, 2015). Therefore, the usefulness of big data for machine learning is largely determined by data quality

Figure 7. AlphaGo is an artificially intelligent computer programme developed by Google DeepMind to play the board game 'Go'. In October 2015, it became the first computer Go programme to beat a human professional Go player.

In summary, the applications of artificial intelligence in manufacturing are expected to increase at a rapid pace due to the increased availability of big data, higher computing power (through, for example, cloud computing) and the development of better machine learning algorithms. In particular, autonomous robotic systems are an excellent candidate for exploiting advances in artificial intelligence and machine learning.

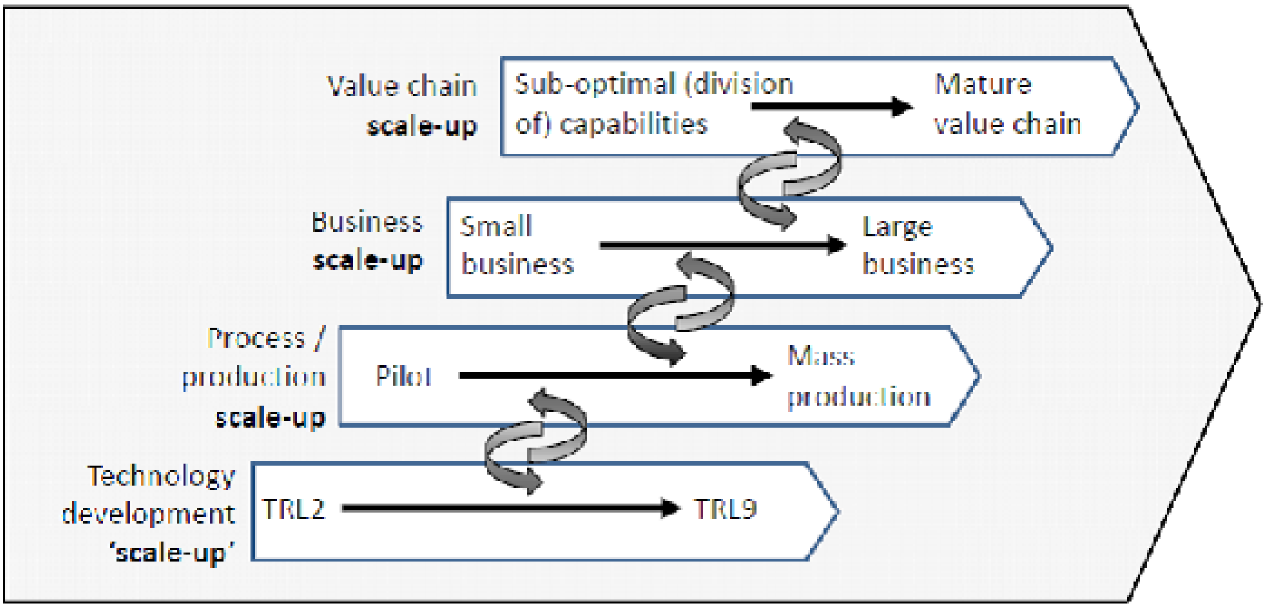
3.3 | Enabling tools and methods for scaling-up novel technologies

An additional common theme discussed in the documents reviewed for this report relates to the challenge of scaling-up and commercialising novel technologies. The term 'scale-up' is used in a variety of ways in literature, with different emphases on particular innovation and industrial activities. A useful definition is offered by the influential report Accelerating U.S. Advanced Manufacturing (PCAST, 2014, p 38):

> *"Scale-up can be defined as the translation of an innovation into a market. There are significant technical and market risks faced by new manufacturing technologies during scale-up. The path to successful commercialization requires that technologies function well at large scale and that markets develop to accept products produced at scale. It is a time when supply chains must be developed, demand created and capital deployed."*

Therefore, scale-up of novel technology is a multi-dimensional occurrence that encompasses four main dimensions, as shown in Figure 8 (O'Sullivan and López-Gómez, 2017):

Figure 8. The multi-dimensional nature of scale-up



Source: O'Sullivan and López-Gómez (2017)

- **Technology scale-up**: The path from laboratory prototype to manufacturing-ready product is full of technical challenges and risks. A range of engineering and scientific resources and services are required to develop a product with the right performance for commercialisation. Quality and health and safety certifications often require additional testing that, if unsuccessful, can kill a product before it reaches the market. Similarly, ensuring that this product is correctly designed for manufacturability often requires working in parallel with people in charge of designing and operating the production processes. In addition to technical difficulties, the capital required to move between technology readiness levels is often significant and any setbacks in the product development phases can lead to unacceptable budget penalties that could stop the technology scale-up process in its totality.

- **Process/production scale-up**: As mentioned above, technology scale-up involves more than product design and development. Mass-scale manufacturing processes need to be prepared to accommodate new products and any manufacturing constraints need to be communicated to product designers for them to ensure the manufacturability of the product. In addition, emerging technologies often require new production processes to be developed or traditional processes to be adapted for them. The tooling costs for mass-scale production of new products is significant and, consequently, considerable effort has to be made in testing and de-risking production through the use of pilot production lines for demonstration and testing. Applied research centres play a key role in demonstrating and de-risking new production technologies.
- **Business scale-up**: The business functions needed to support technology and production scale-up, including technical, organisational and operational capacities, have to be scaled-up in parallel with the development of products and production technologies. However, this is often a challenging task: skilled and experienced labour is not always available to cover all the required business functions; access to finance is not always straightforward; and entering new markets can be challenging when facing more well-established competition.
- **Value chain scale-up**: No product can reach the market without first developing an appropriate value chain with the right suppliers for both production inputs (e.g. raw materials and/or components) as well as capital equipment. Closely interconnected supply chains are essential to ensure the successful scale-up of new technologies into mass-scale products, as their successful production often requires significant innovation efforts from suppliers.

> ***“Full technology commercialisation not only requires technology to be matured to function well at large scale, it also needs the scale-up of appropriate manufacturing processes and value chains for large-scale production, as well as the scale-up of business functions to support those activities. Therefore, scale-up of novel technology is a multi-dimensional occurrence.”***

> ***“Recent international efforts to facilitate the scale-up of novel technologies have focused on the creation of applied research centres with the mission to create novel tools and testing facilities to demonstrate and de-risk emerging technologies. Examples of enabling solutions for scale-up include advanced metrology, real-time monitoring technologies, characterisation protocols, analysis and testing tools, open databases (e.g. material property databases), and modelling and simulation tools.”***

Recent international efforts in this area have focused on the creation of applied research centres with the mission to create novel tools and testing facilities to demonstrate and de-risk emerging technologies. This often includes investment in pilot production lines capable of scaling-up new innovations in readiness for large-scale production. An overview of three applied research centres are presented in Section 5 – the National Network for Manufacturing Innovation in the USA (also known as Manufacturing USA), the High Value Manufacturing Catapult Network in the UK and the Pilot Lines initiative funded by the European Commission.

Due to the diversity of fields from which novel technologies can emerge, it is difficult to identify cross-cutting technologies, tools and solutions that can be employed in a universal way to aid in their scale-up process. However, some general enabling technologies have been identified, including advanced metrology, real-time monitoring technologies, characterisation protocols, analysis and testing tools, open databases (e.g. material property databases), and modelling and simulation tools (O'Sullivan and López-Gómez, 2017). In particular, the Factories of the Future initiative by the European Commission (2013) mentions modelling and simulation tools as well as advanced metrology as key enabling technologies of significant importance for the scale-up of novel innovations across a range of distinct fields. The following sections discuss these two enabling technologies in further detail.

Modelling and simulation tools

In manufacturing, computer-based modelling and simulation refers to obtaining information about how manufacturing products, processes or systems behave without actually physically testing them in a real environment. This minimises the time and cost associated with physical testing. The information provided by these models and simulations is a valuable input to inform engineering and managerial decisions.

Despite their potential for reducing costs, improving quality, and shortening the time-to-market for manufactured goods, these tools remain largely underutilised by industry today (HMVC, 2017). However, through the digitalisation of manufacturing, it is expected that these benefits will grow as future modelling and simulation tools become more accessible and are developed for all levels of the factory and its life cycle, including the co-design and management of integrated product–process–production systems (European Commission, 2013).

Factories equipped with digital technologies (such as the ones discussed in Section 3.2.3) will be able to support real-time decision making processes for operation planning and control that will enable faster scale-up and reduced time to market (European Commission, 2013). Virtual factory models will allow planners to test and optimise factory design and performance before the real factory is built, saving time to production (European Commission, 2013). These virtual models will be maintained once the factory is established in order to virtually test and vali-

> ***"Computer-based modelling and simulation refers to obtaining information about how manufacturing products, processes or systems will behave without actually physically testing them in a real environment, minimising the time and cost associated with physical testing."***

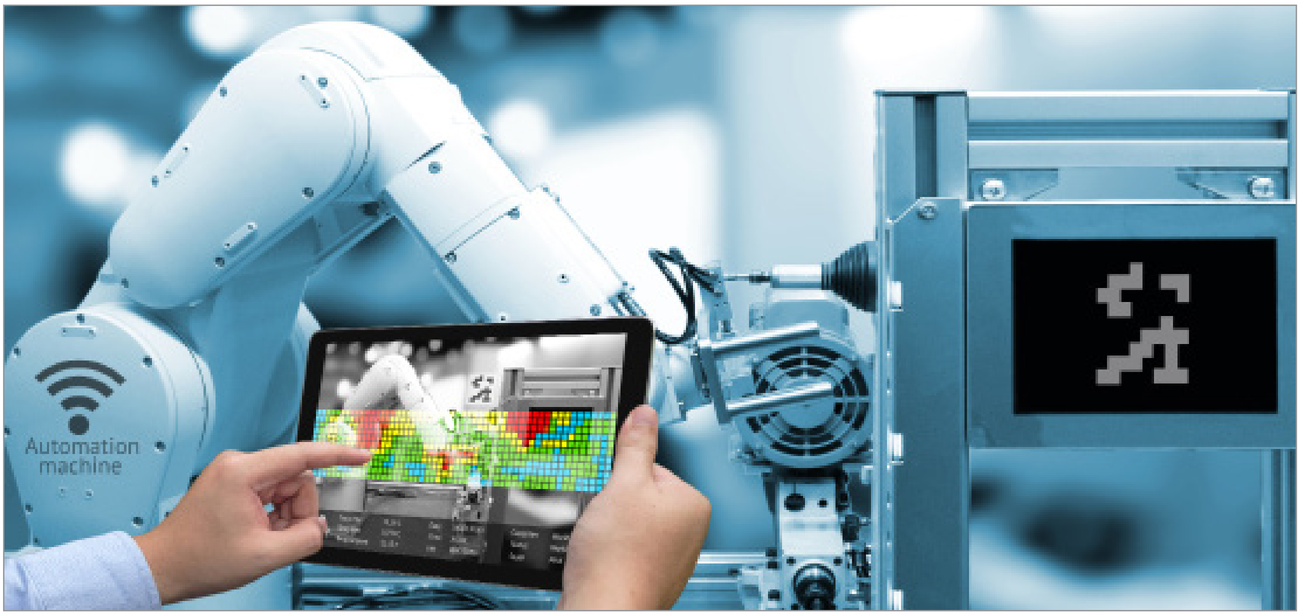
date reconfiguration options, leading to shorter implementation times in the real factory (European Commission, 2013).

More sophisticated modelling and simulation tools lead to computational complexity that needs to be addressed. Similarly, increased sensing and access to data leads to big data problems such as having more unstructured and heterogeneous data that needs to be verified to ensure model correctness and resilience, as previously discussed in Section 3.2.3 (NSF, 2015a). Future models and simulations will aim to characterise and mitigate uncertainty and variability in the operation of manufacturing processes by using historical data to develop uncertainty and variability models. A fundamental area of future research focus will be the expansion of current models towards systems of larger scale, which presents challenges for process control and optimisation. In particular, work is required in order to control large scale non-linear, variable and hybrid systems (NSF, 2015a).

Advanced metrology

Metrology, known as the science of measurement (Howarth and Redgrave, 2008), is separated into three broad categories that include scientific metrology (organisation and development of measuring standards); industrial metrology (calibration and functioning of measurement instruments employed in industry); and legal metrology (legal verification of measurement instruments that can influence the transparency of economic transactions) (Howarth and Redgrave, 2008).

Figure 9. Modelling and simulation tools will allow the virtual testing and optimisation of production processes to reduce cost and improve quality



In addition to providing important calibration, testing and measurement functions to ensure the quality of industrial activities, metrology provides key measurement standards for existing and emerging fields, including (Howarth and Redgrave, 2008):

- Mass and related quantities
- Electricity and magnetism
- Length
- Time and frequency
- Thermometry
- Photometry and radiometry
- Flow
- Acoustics, ultrasound and vibration
- Chemistry

"Metrology, known as the science of measurement, provides important calibration, testing and measurement functions to ensure the quality of industrial activities, in addition to developing appropriate measurement standards for emerging technologies."

Advanced metrology R&D focuses on developing next-generation measurement instruments, smart software and hardware and new metrology methodologies that could enable the 'factory on the machine' concept – i.e. the ability to manufacture, measure and correct in a single process to enable 'right first time and every time' fabrication of manufacturing goods (CIMAM, 2016). This 'factory on the machine' concept would minimise machine tool downtime and generate considerable cost savings by allowing the measurement, inspection and correction of components in one single process, compacting and accelerating the production chain.

Specific areas of research in advanced metrology include sensor technologies for precision machining, rapid machine tool calibration for in-process inspection, interferometry with vibration reduction for in-process surface characteristics, mathematics for metrology, optical instruments, surface metrology and intelligent calibration decision making, among others (CIMAM, 2016).

4 | Challenges and opportunities in advanced manufacturing: framing research and innovation policies

OVERVIEW OF THIS SECTION

- This section discusses challenges and opportunities in advanced manufacturing for firms and countries in the context of intense international competition and rapid technological change.
- Emphasis is made on ways in which firms capture value in modern manufacturing. This discussion is framed around four advanced manufacturing perspectives:
    - Product innovation – competing on speed of new technology development
    - Process innovation – competing on product mix flexibility and factory productivity
    - Supply chain – competing on reconfigurable supply chain capabilities
    - Customer demand – competing on superior customer demand knowledge and levels of satisfaction
- Internationally, it is increasingly recognised the policy challenge to support advanced manufacturing innovation involves not only funding R&D, but also supporting the scale-up of emerging technologies; promoting commercialisation by business and technology adoption by SMEs; as well as fostering 'balanced' regional development.
- It is hoped that the analysis presented in this section can help policy-makers frame the potential missions and impacts of policies, initiatives and programmes designed to support advanced manufacturing.

4.1 | Introduction

Given the current global industrial context, three factors make the design of policies to support advanced manufacturing challenging:

- Increasing complexity of manufacturing systems
- Changing dynamics of value capture across sectors
- Increasing number of players (i.e. emerging economies) in advanced manufacturing

An initial complication in the design of advanced manufacturing policies has to do with the fact that modern manufacturing industries – the systems that policies are expected to influence – are themselves becoming increasingly complex. There is broad agreement that the boundaries of manufacturing as an economic activity are increasingly blurry and that advanced manufacturing is in fact inherently multi-dimensional (Box 9). This has practical implications for policy-makers in terms of the type of evidence required to understand current capabilities, sources of high-value

> *"There is broad agreement that the boundaries of manufacturing as an economic activity are increasingly blurry and that advanced manufacturing is in fact inherently multidisciplinary."*

within industries, and the effects of market failures. There are also implications for the way in which boundaries of sector-specific programmes should be defined, and the range of technologies and research areas that need to be considered in advanced manufacturing initiatives.

A second factor driving complexity in policy design for advanced manufacturing is the continuous change in the dynamics of value capture across industries. Megatrends discussed in previous sections, and the growing interdependencies in manufacturing, mean that the scope for innovation is becoming broader and the ways in which value can be captured more diverse. Programmes focused on aerospace and automotive, for example, need to account for trends in technologies that are capturing an increased share of value added within those industries, such as advanced materials and artificial intelligence. However, they also need to account for developments in closely-related sectors such as electronics and advanced machinery. Moreover, manufacturers are increasingly gaining additional revenue streams by offering services related to their products and by developing new disruptive business models (RAE, 2012; Neely et al, 2011). In this complex and changing context, it is still unclear who the winners (and losers) across industries and nations will be, and the role that policy-makers can play in determining this balance.

"Policy-makers require sharper insights into international developments, not only to assess the competitive position of domestic industries, but also to better understand potential impacts of interventions in industries with global supply chains."

BOX 9. WHAT IS ADVANCED MANUFACTURING ANYWAY?

Unlike the vertically integrated configurations of manufacturing in the 20th century, modern manufacturing systems are characterised by increasingly complex interdependencies distributed across a range of industries, firms, technologies, subsystems, and components (PCAST, 2011; Tassey, 2010; Brecher, 2012). Traditional representations of manufacturing, based on a well-defined industrial sector and academic discipline boundaries, are unable to fully characterise the complexity involved in bringing about manufactured products and services (BIS, 2012; NAE, 2015).

Against this backdrop, the definitions adopted across countries vary. In the USA, the discourse on manufacturing is dominated by discussion of advanced manufacturing, often highlighting the importance of manufacturing information technology systems or emerging science-based technologies. In Japan, the term 'monozukuri', although often translated as 'manufacturing', has a particular emphasis on the importance of high quality craftsmanship, design and integration engineering. In Germany, the term 'produktionssysteme und -technik' typically emphasises production technologies, machine tools and factories (O'Sullivan and Mitchel, 2013).

A recent report for the USA President's Council of Advisors on Science & Technology defines advanced manufacturing as:

> *"The family of activities that (a) depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or (b) make use of cutting edge materials and emerging capabilities enabled by the physical/biological sciences, e.g. nanotechnology, chemistry, and biology. This involves both new ways to manufacture existing products, and especially the manufacture of new products emerging from new advanced technologies"* (PCAST, 2011).

A third factor making it increasingly complex to design effective advanced manufacturing policies is the increasing number of players in advanced manufacturing. A global redistribution of manufacturing value and employment has been going on for decades, and emerging manufacturing countries traditionally focused on low value-added activities are making strides into more advanced areas. As such, the context in which modern policy making takes place is one of increasing competition for the industrial activities with the most high value capture potential. Large-scale investments in China's aerospace industry, for example, have important implications for aerospace industries around the world, from France and the UK to Canada and Brazil. With the potential rise of protectionist measures across global economic blocks, policy-makers require sharper insights into international developments, not only to assess the competitive position of domestic industries, but to also better understand potential impacts of interventions in industries with global supply chains.

4.2 | Implications for advanced manufacturing research and innovation policies

From a research and innovation policy perspective, understanding the impact of institutions, programmes and initiatives focused on advanced manufacturing requires more sophisticated policy frameworks based on a detailed understanding of modern manufacturing systems.

Firstly, it is necessary to understand that many of the solutions for future advanced manufacturing challenges might not be resolved by a single R&D breakthrough or technology. Solutions to industrial challenges driving productivity and industrial competitiveness will increasingly come from combinations of technologies and involve multiple research domains (OECD, 2016; O'Sullivan, 2011). For example, making cars more fuel efficient will require integrated R&D effort across areas such as high-fidelity aerodynamics, advanced materials (e.g. composites), advanced systems integration, and next-generation batteries and fuel cells.

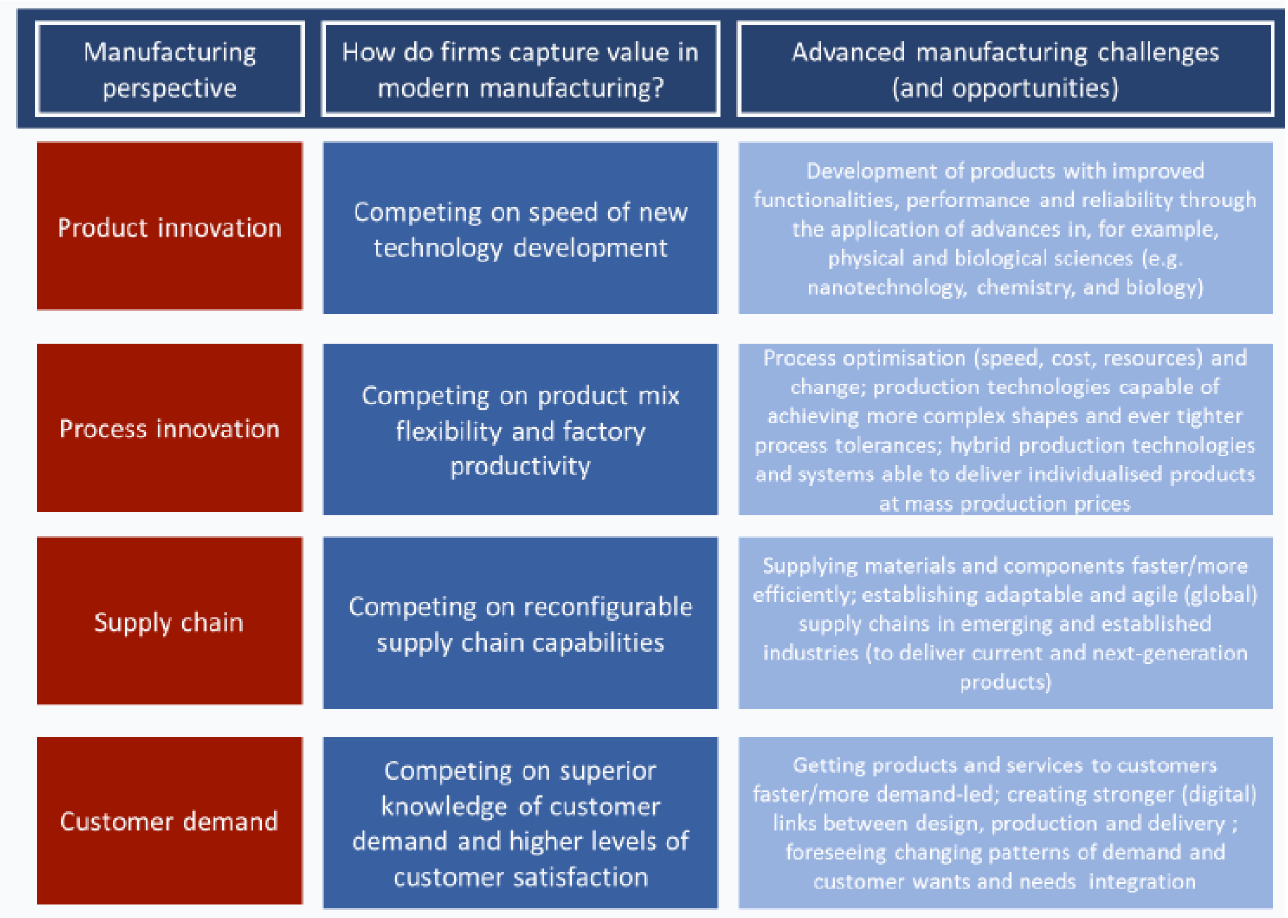
Secondly, certain technologies are expected to have pervasive effects and underpin capabilities across a range of sectors. For example:

- Advances in ICT have the potential to provide new possibilities across manufacturing sectors and activities
- Material modelling and simulation tools are changing the way products are designed
- Automation and real-time process monitoring are driving factory-level productivity
- Advanced enterprise resource planning is making supply chains more resilient
- Big data analytics are giving firms more insights into the features and quantities that customers want

4.3 | Capturing value through advanced manufacturing research and innovation

Recent national analyses of manufacturing have given careful attention to identifying those elements of advanced manufacturing systems with the most potential to capture significant value for the domestic economy (OECD, 2016). This section reflects on these discussions, as well as the trends and drivers discussed earlier in the report, and distinguishes four advanced manufacturing perspectives that can be useful to characterise research and innovation policies in terms of missions, technology focus and industrial impact. These perspectives correspond to different types of manufacturing activities and capabilities underpinning advanced manufacturing systems. As described in Table 2, they provide a structure to describe the different ways in which firms capture value in modern manufacturing – and the potential focus of advanced manufacturing policies.

Table 2. Capturing value through advanced manufacturing research and innovation



Manufacturing perspective	How do firms capture value in modern manufacturing?	Advanced manufacturing challenges (and opportunities)
Product innovation	Competing on speed of new technology development	Development of products with improved functionalities, performance and reliability through the application of advances in, for example, physical and biological sciences (e.g. nanotechnology, chemistry, and biology)
Process innovation	Competing on product mix flexibility and factory productivity	Process optimisation (speed, cost, resources) and change; production technologies capable of achieving more complex shapes and ever tighter process tolerances; hybrid production technologies and systems able to deliver individualised products at mass production prices
Supply chain	Competing on reconfigurable supply chain capabilities	Supplying materials and components faster/more efficiently; establishing adaptable and agile (global) supply chains in emerging and established industries (to deliver current and next-generation products)
Customer demand	Competing on superior knowledge of customer demand and higher levels of customer satisfaction	Getting products and services to customers faster/more demand-led; creating stronger (digital) links between design, production and delivery ; foreseeing changing patterns of demand and customer wants and needs integration

Source: López-Gómez and O'Sullivan (2017).

Product innovation: competing on speed of new technology development

In the context of growing international competition, there is recognition among policy-makers that capturing value from manufacturing increasingly relies on the ability to apply technological developments in advanced products and solutions that were not previously possible (PCAST, 2014). There is emphasis on the technological race to apply advances in emerging fields including advanced functional materials, novel biotechnology (e.g. synthetic biology and regenerative medicine), photonics and naotechnology to develop new high-value products and processes.

As discussed in the case studies in the next section, an important component of these endeavours is research investments in novel production technologies and infrastructure (e.g. pilot production lines) to support the accelerated industrialisation of novel emerging technologies.

The policy discourse on manufacturing in the USA, for example, has been recently dominated by discussions of advanced manufacturing, which often highlight the importance of emerging science-based technologies, and the particular opportunities for the USA to take advantage of the nation's leading research position in universities and public and private research centres to drive the creation of next-generation products and industries (O'Sullivan & Mitchel, 2013).

In this context, many governments are giving increasing importance to public (or public-private) investment in R&D that translates a laboratory environment prototype into a system ready for commercial deployment (PCAST, 2014; Hauser, 2010, 2014; Foresight, 2013). The risk of market failure inhibits individual private sector businesses from investing in pilot production lines or in developing the engineering tools required to scale-up and industrialise many important new technologies.

> *"Capturing value from manufacturing increasingly relies on the ability to apply technological developments in advanced products and solutions that were not previously possible."*

In view of this, there are increasing efforts in many countries to create new public-private partnerships and institutions to overcome these market failures. In particular, there is increasing interest in institutions and programmes undertaking manufacturing-related R&D past the proof-of-concept level to technology validation, prototype demonstration and system prototype demonstration in operational environments. The progress of a new technology from foundational research to commercial-readiness is measured by a Technology Readiness Rating, which has nine readiness levels – TRL 1 is the lowest and TRL 9 is the highest. The focus for applied R&D is on Technology Readiness Levels 4-7. There is also growing attention on programmes and institutions that can support efficient and effective transitions between the various TRL levels (Foresight, 2013).

Process innovation: competing on product mix flexibility and factory productivity

The characteristics of production technologies and the systems needed to enable manufacturing to remain competitive in high-wage economies are a concern to policy-makers as detailed in recent policy documents. Traditional manufacturing solutions to changing demands, such as machining centres and flexible manufacturing cells, are limited. As highlighted earlier in this report, opportunities to capture value through production processes that are able to produce individualised products at mass production prices will deliver a competitive advantage to a manufacturer. Achieving both economies of scale and scope to enable participation in both niche and volume markets is the aspiration (Brecher, 2015; Klocke, 2009; RWTH, 2015).

In this context, it is recognised that many production system innovations are likely to come from production technology firms providing technological, system or process solutions in response to the needs of consumer industries (Westkämper, 2014).

In Germany, for example, considerable efforts are being directed towards understanding how integrative production technologies and ICT enabled planning and management may underpin sustainable competi-

> *"Many production system innovations are likely to come from production technology firms providing technological, system or process solutions in response to the needs of consumer industries."*

tive advantage in manufacturing (Brecher, 2012, 2015). Research efforts include the integration of multiple technologies to develop virtual, hybrid and self-optimising production systems, as well as the optimisation of factory layouts.

Step changes in operational efficiency can also be expected from:

- Extended use of embedded systems, robotics and artificial intelligence
- Intensive vertical integration of manufacturing processes (increased connectivity of factory processes)
- Increased deployment and integration of sensors that will underpin new real-time process control capabilities, and inform smarter predictive actions

All these developments are being accelerated by the continuous reduction in the price of sensors and actuators with potential use across manufacturing operations.

Supply chain: competing on reconfigurable supply capabilities

Because of the increasing complexity of some products and the knowledge and skills required in their assembly, many manufacturers believe that their company's competence and value lies in their supply chain integration and diversification capabilities. The traditional focus of operations management has been flexibility in supply chains, which is critical to deal with market fluctuations and control inventories. Emphasis has been made on adaptable and agile supply chains to generate profits by eliminating waste caused by over-production.

> ***"Suppliers able to provide new materials, parts and components (often required to conform to more stringent performance standards) are needed in order to deliver next-generation products and related services."***

In the context of rapid technological change, however, targeting new value opportunities triggers the need for supply chains to upgrade and diversify. Suppliers able to provide new materials, parts and components (often required to conform to more stringent performance standards) are needed in order to deliver next-generation products and related services. Therefore, national and regional supply chain ecosystems are likely to differentiate themselves by their ability to build on current strengths and reconfigure capabilities for new opportunities faster than competitors (CSTI, 2015b).

Advances in hybrid production technology such as the ones discussed previously in this section also have the potential to redefine the labour requirements and lead times for factory operations, potentially affecting global value chain configurations. For example, a laser heat treatment can be integrated into a machining process in the same manufacturing equipment, thereby eliminating steps, reducing changeover times, and shortening the supply chain (RWTH, 2015). Hybrid technology has attracted the interest of advanced economies looking to retain high value manufacturing activities domestically (O'Sullivan and López-Gómez, 2017).

New opportunities to increase supply chain adaptability and agility are also being driven by new software solutions that allow manufacturers to 'virtualise' global production networks and optimise collaborations along the supply chain. Such tools can help companies uncover capacity problems and issues within the general workflow across global supply chains (Schuh et al. 2013). As products and production systems become more complex, new ways of integrating engineering systems will enable technology convergence and the transferring of globally dispersed capabilities throughout the global supply chain. New intelligent logistics will also increase the visibility, control and traceability of inputs via the integration of software, hardware and standards.

Customer demand: competing on superior customer satisfaction

In an increasingly competitive manufacturing environment, companies and governments have been turning their attention to displacing their competitors through superior customer satisfaction. Manufacturers are exploring tools for personalised product design, design management and on-demand manufacturing of customised products. As a result, both the public and private sectors have invested in research environments that encourage consumers to engage and interact with manufacturers, such as living labs, open innovation centres and joint public-private manufacturing research institutions (O'Sullivan, 2016).

New digital platform businesses such as Google or Amazon, which create value by facilitating exchanges between sellers and consumers, are emerging as both potential competitors and partners of manufacturers. The potential opportunities and challenges that platform businesses present manufacturers have been recognised by some governments, including the Japanese Government, which is undertaking multidisciplinary research to understand and define platform businesses and their implications for manufacturing (CRDS, 2015).

> ***"In several countries increasing attention is being paid to 'customer-focused' research endeavours, including tools for personalised and innovative product design upstream design management and on-demand manufacturing of customised products."***

Furthermore, the advanced manufacturing-related strategies of some countries highlight the interdependence of manufacturing competencies (tools, techniques and processes) with design, research and innovation. Some of these opportunities will be enabled through the digitalisation of manufacturing and the ability to share data and model systems more effectively. For example, a central theme in Japan's cross-ministerial Strategic Innovation Promotion Programme (SIP) is the integration of innovative design and manufacturing technologies (CSTI, 2015a), as discussed in Section 6.

4.4 |The policy challenge: Beyond R&D funding

Because the challenges described above are interrelated, it can be argued that the ability to capture value from innovation in advanced manufacturing is likely to require an integrated approach to:

- Develop new technologies and embed them in products
- Apply new knowledge and skills to industrial processes
- Develop adaptable and agile supply chains, and
- Deliver products and services that satisfy changing customer needs at the right time and at the right price

It can be further argued that, in the context of a global race for value capture, the ability to tackle these capability challenges faster than competitors is set to become an increasingly important source of differentiation.

As recognised by many governments across the world, focusing on technology development is not enough to realise an economic impact and, thus, economic growth. A wider range of innovation activities is required to support the emergence of new industries and the upgrading of established ones. The policy challenge involves not only funding basic and applied R&D, but also supporting the scale-up of emerging technologies, promoting commercialisation by business and adoption by SMEs, as well as developing more competitive domestic industries while fostering balanced regional development.

5 | Making an impact: Emerging policy approaches for advanced manufacturing research and innovation

OVERVIEW OF THIS SECTION

- This section presents a selection of advanced manufacturing initiatives and programmes. While the choice of interventions largely reflects countries' particular industrial and innovation structures as well as particular national priorities, it is hoped that the cases presented provide an international context and illustrate differences in international policy approaches.
- Examples from the UK, USA, China, Germany and Japan are presented, as summarised below.

Advanced manufacturing initiative (country)	Description	Advanced manufacturing perspective emphasis			
		Product innovation	Process innovation	Supply Chain	Customer Demand
High Value Manufacturing Catapult (UK)	Network of Government-supported applied research centres promoting business-led collaboration between scientists, engineers and industrialists	xx	xxx	x	
Manufacturing USA Institutes (USA)	Network of linked advanced manufacturing institutes aimed at addressing the investment gap in pre-competitive applied R&D, and de-risking new technology and material scale-up	xx	xxx	xx	
National Manufacturing Innovation Centres (China)	Innovation centres focused on boosting technology and innovation in key areas such as next-generation ICT, smart manufacturing, new materials, additives and pharmaceuticals	xx	xxx	x	
Cluster of Excellence in Integrative Production Technology for High-Wage Countries (Germany)	Manufacturing research cluster focused on new technologies required to address the future individualisation, hybridisation and self-optimisation of production.	x	xxx	x	xx
Intelligent Technical Systems OstWestfalenLippe alliance (Germany)	Consortium of private and public technological innovation organisations that focus on key manufacturing digitalisation topics at the heart of Industry 4.0.	xxx	xx	xxx	x
Cross-Ministerial Strategic Innovation Promotion Programme (Japan)	National innovation programme including advanced manufacturing themes focused on improving the digital links between R&D, design and production for faster scale-up of new technologies.	xx	xx	xx	xx
Notes xxx Primary emphasis xx Secondary emphasis x Minor emphasis	**Advanced manufacturing perspectives (see Section 4)** **Product innovation** – competing on speed of new technology development **Process innovation** – competing on product mix flexibility and factory productivity **Supply Chain** – competing on reconfigurable supply chain capabilities **Customer demand** – competing on superior knowledge of demand and higher levels of satisfaction				

5.1 | Introduction

This section reviews a selection of advanced manufacturing programmes and initiatives in important manufacturing economies to illustrate how policy-makers are responding to advanced manufacturing challenges and opportunities in the context of a changing global industrial context. The review focuses on specific programmes managed by governments or government related institutions with a direct impact on advanced manufacturing. In other words, the review does not take into account other policies and programmes in areas such as trade policy or tax policy that may also have an impact on advanced manufacturing.

> ***"The case studies highlight a diversity of emphases across advanced manufacturing perspectives: product innovation, process innovation, supply chain and customer demand."***

Several institutions play a critical role in designing and implementing advanced manufacturing strategies. Universities, science and economy ministries, R&D and innovation agencies, intermediate research institutes, and standards development bodies, among others, might all be involved either individually or collectively in delivering national and regional innovation agendas. Institutional structures and practices in all these organisations are shaped by historical industrial strengths, innovation priorities, and the particular characteristics of the institutional infrastructure in each country (O'Sullivan, 2011, 2016).

Many of the programmes discussed here have only been recently established and therefore it is difficult to offer conclusions about effectiveness or best practices. Instead, the case studies highlight a diversity of emphases across the advanced manufacturing perspectives discussed in the previous section (product innovation, process innovation, supply chain and customer demand). The cases also illustrate the diversity of activities beyond R&D that advanced manufacturing programmes and initiatives are carrying out to support industrial innovation.

The cases discussed in this section are:

- High Value Manufacturing (HVM) Catapult (UK)
- Manufacturing USA Institutes (USA)
- National Manufacturing Innovation Centres (China)
- Cluster of Excellence in Integrative Production Technology for High-Wage Countries (Germany)
- Intelligent Technical Systems OstWestfalenLippe (Germany)
- Cross-Ministerial Strategic Innovation Promotion Programme (Japan)

5.2 | High Value Manufacturing (HVM) Catapult centres (UK)

The UK's High Value Manufacturing (HVM) Catapult centres are a network of seven applied R&D centres set-up to promote research and innovation through business-led public-private collaborations (Innovate UK, 2015). The centres were originally conceived to deliver "a step change in the UK's ability to commercialise its research" (Hauser, 2010). Catapult centres are aimed at helping fill in the 'missing middle' between basic research and private sector commercialisation.

They act as bridge between businesses and the research and academic communities to enable projects that no single actor would be able to perform by itself (Policy Links, 2015).

The number of Catapult centres has been increasing since the programme was announced in 2010. There are currently 11 centres:

- Cell and Gene Therapy
- Compound Semiconductor Applications
- Digital
- Energy Systems
- Future Cities
- High Value Manufacturing or HVM (a network of another seven centres)
- Medicines Discovery
- Offshore Renewable Energy
- Precision Medicine
- Satellite Applications
- Transport Systems

Each Catapult centre specialises in a different area of technology, but with a common focus on supporting the development of new products and services on a commercial scale.

In particular, the HVM Catapult network has been conceived with the aim of strengthening the national infrastructure supporting advanced manufacturing. The network consists of seven individual centres with distinct competencies, but with a shared focus on tackling industry-relevant problems and addressing market failures that prevent the rapid development and commercialisation of advanced product and manufacturing-process innovations.

The HVM Catapult's distinct technological focus and capabilities offers manufacturing firms access to facilities to scale-up and prove-out high-value manufacturing processes across different technology areas.

The seven HVM Catapult centres are the:

- Advanced Forming Research Centre (AFRC)
- Advanced Manufacturing Research Centre (AMRC)
- Centre for Process Innovation (CPI)
- Manufacturing Technology Centre (MTC)
- National Composites Centre (NCC)
- Nuclear Advanced Manufacturing Research Centre (NAMRC)
- Warwick Manufacturing Group (WMG)

> ***"The High Value Manufacturing Catapult network consists of seven individual centres with distinct competencies, but with a shared focus on addressing market failures that prevent the rapid development and commercialisation of advanced product and manufacturing-process innovations."***

A good illustration of a HVM Catapult centre is the MTC, originally founded by the University of Birmingham, Loughborough University, the University of Nottingham and private firm TWI Ltd. The MTC specialises in manufacturing technologies and processes including: intelligent automation, advanced tooling; high integrity fabrication; simulation and informatics; advanced metrology; and additive manufacturing. One example of process innovation projects is the development of additive layer manufacturing (ALM) for large structural engine components in collaboration with companies such as Rolls-Royce (HVMC, 2017).

In 2014, the MTC launched the UK's first digital factory demonstrator. In collaboration with other HVM Catapult centres, it carries out projects in advanced immersive visualisation to support new product development, with solutions including factory layout planning, virtual prototyping and assembly training.

The Catapults also engage in innovation activities beyond R&D, including the development of supply chains and specialised technician training. A recent independent review highlighted the Catapult network's positive contribution to industry in the UK and called for the establishment of additional centres (Hauser, 2014).

5.3 | Manufacturing USA institutes (USA)

Manufacturing USA is a network of linked manufacturing innovation institutes. Each institute provides shared facilities to local start-ups and small manufacturers to help them scale-up new technologies, accelerate technology transfer to the marketplace and facilitate the adoption of innovation workforce skills (AMNPO, 2017).

The goals of the Manufacturing USA institutes include:

- Address the market failure of industry underinvestment in pre-competitive applied R&D
- De-risk new technologies and materials to scale-up for USA manufacturers
- Create the space for industry and academia to collaborate

Following the launch of the initiative in 2012, major institutes have been funded in the following domains: additive manufacturing; integrated digital design and manufacturing; lightweight technology; wide bandgap semiconductors; advanced polymer composites and, most recently; integrated photonics and smart manufacturing. The President's 2017 Budget proposes nearly US$2 billion for the National Network for Manufacturing Innovation (AAAS, 2016).

In June 2016, the White House also announced plans for five additional hubs: a Robotics in Manufacturing Environments Manufacturing Innovation Institute; an Advanced Tissue Biofabrication Manufacturing Innovation Institute; a Modular Chemical Process Intensification (MCPI) Institute; and a Reducing Embodied Energy and Decreasing Emissions (REMADE) in Materials Manufacturing Institute (White House, 2016).

Similar to the Catapult centres, the Manufacturing USA institutes have a strong focus on pro-

> ***"Manufacturing USA institutes provide shared facilities to local start-ups and small manufacturers to help them scale-up new technologies, accelerate technology transfer to the marketplace and facilitate the adoption of innovation workforce skills."***

cess innovation. An example is the Power America institute, which focused on next-generation power electronics. The institute's mission is to develop advanced manufacturing processes that will enable large-scale production of wide bandgap semiconductors. This, in turn, is expected to allow power electronics components to be smaller, faster and more efficient than silicon.

5.4 | National Manufacturing Innovation Centres (China)

China's Made in China 2025 industrial innovation strategy has been inspired to a large extent by Germany's Industry 4.0 (O'Sullivan, 2016; Wübbeke et al, 2016). Made in China 2025 includes plans to set up 15 National Manufacturing Innovation Centres by 2020, which will be further increased to 40 by 2025. These centres build on recent Chinese policies that explore new models of industrial innovation via strategic alliances.

The first National Manufacturing Innovation Centre, the National Power Battery Innovation Centre (NPBIC), launched in 2016, illustrates the focus on both product and process innovation of the initiative. The NPBIC's mission is to accelerate the industrialisation of innovative battery technologies and enhance the competitiveness of China's power battery industry, not only through R&D, but also by providing testing services, pilot-scale experiments and industry support services.

The Made In China Innovation Centres are expected to focus on boosting technology and innovation in areas such as next-generation ICT, smart manufacturing, new materials, additives, and pharmaceuticals. The USA National Manufacturing Innovation Institutes (see above) are often cited as comparable in terms of rationale and functions.

Although details about the National Manufacturing Innovation Centres are still scarce – in terms of detailed planned budgets, scale, longevity or key performance indicators – the programme design does appear to reflect important themes that have also arisen in a number of other countries, in particular:

- Attention to **manufacturing scale-up**, focusing on building a critical mass of multidisciplinary engineering R&D capabilities to **accelerate the industrialisation of key generic industrial technologies**
- Efforts to deploy a greater range of scientific and technological resources to address industry-relevant engineering R&D challenges by building stronger linkages and **alliances between universities and firms, but also public research institutes**
- **Flexibility and freedom to experiment with organisational models** for effective industry-academia-research cooperation.

> *"China's National Investment Fund for Advanced Manufacturing Industry alone has an allocated budget of €2.7 billion, and the National Integrated Circuit Fund received €17.6 billion. These are further complemented by a variety of significant provincial level funding schemes."*

It is worth noting that, in comparison to programmes in other countries, the financial resources that have been announced to implement the Made in China 2025 strategy are quite substantial.

For instance, China's National Investment Fund for Advanced Manufacturing Industry alone has an allocated budget of €2.7 billion, and the National Integrated Circuit Fund received €17.6 billion (Wübbeke et al, 2016). These are further complemented by a variety of significant provincial level funding schemes. In comparison, the public component of the initial funding for Industry 4.0 in Germany amounted to around €200 million.

5.5 | Cluster of Excellence Integrative Production Technology for High-Wage Countries (Germany)

The Aachen Cluster of Excellence Integrative Production Technology for High-Wage Countries is a major manufacturing research centre initiative funded by the German Research Foundation. It represents an important effort towards achieving the Industry 4.0 vision. The cluster is part of a €180 million investment awarded to RWTH Aachen University to fund education, research and innovation (RWTH, 2015).

The goal of the initiative is to maintain production in high-wage countries by developing new sustainable production strategies and theories. The cluster brings together 25 research departments from Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen University and other research institutions and seeks active collaborations with industrial partners.

The cluster carries out highly interdisciplinary scientific work around four core areas (RWTH, 2015):

> ***"The goal of the Aachen Cluster of Excellence is to maintain production in high-wage countries. Its research focuses on developing new manufacturing technologies to address the future individualisation, virtualisation, hybridisation, and self-optimisation of production."***

- **Individualised production:** Refers to how small batches of customised products can be produced efficiently and at competitive prices. The key research focus is on technological changes that would enable a radical reduction in the time required to take a product idea to production. An example technology developed in this area is an additive manufacturing process known as Selective Laser Melting (SLM). This process enables small-batch production of individualised products with complex geometries that cannot be produced with standard manufacturing methods.
- **Virtual production systems**: Deals with the development of virtual models for production systems and value chains that can be used to optimise their operation from the conception phase. Virtual models allow designers and planners to test alternative set-ups and design choices without having to carry out physical testing, providing significant cost and time advantages. This research area is heavily related to digitalisation technologies discussed earlier in this report. Example projects in this area include the visualisation of workplace behaviour in individual manufacturing processes as well as full factory logistics.
- **Integrated technologies**: The aim of this research area is to achieve multi-technology production systems that allow various processing steps to happen in one machine, often simultaneously, leading to a significant contraction of the value chain. An example project in this

area is the development of an integrated system that combines machining processes with laser heat treatments, shortening the production chain and improving productivity.

- **Self-optimising production systems**: This area deals with the development of production systems with the ability to adapt to changing conditions by making autonomous decisions in real-time. As in the case of virtual production systems, this research area is strongly related to digitalisation technologies, in particular the retrieval of adequate data from sensors, the correct transmission and conditioning of this data, and its real-time analysis to enable fast artificial intelligence decision-making and adaption.

In addition to research, the cluster provides training, consulting and exchange services in support of industrial partners. Furthermore, a number of centres and spin-off companies have originated from its research activities, with innovations in specific products, processes and technologies (RWTH, 2015).

5.6 | Intelligent Technical Systems OstWestfalenLippe consortium (Germany)

The Intelligent Technical Systems OstWestfalenLippe (It's OWL) consortium is one of the most representative programmes of Germany's Industry 4.0 initiative. The consortium involves a collaboration of 174 businesses, universities and institutes, funded through the German Federal Ministry of Education and Research's (BMBF) Leading-Edge Cluster programme.

It's OWL was named a Leading-Edge Cluster in the third round of the competition in early 2012. It received €100M over five years, funding 46 research projects to develop intelligent technical systems. The project aims to build on the existing manufacturing and innovation capabilities of the OstWestfalenLippe region, which has industrial strengths in mechanical engineering-related sectors and domestic appliances. In terms of research, its strengths are on the interrelated fields of self-optimisation, cognition and industrial automation.

The It's OWL initiative focuses on key digitalisation topics at the heart of Industry 4.0. The consortium uses the concept of 'intelligent technical systems' to describe systems that arise from the interplay of engineering and ICT. As defined, such systems adapt autonomously to the environment and the needs of users, cope with unexpected situations, and are both energy-efficient and reliable. Key research areas addressed by the consortium include: self-optimisation, human-machine interaction, intelligent networking and energy efficiency.

> *"It's OWL research projects focus not only on product innovation itself, but also the development, deployment, maintenance and life cycle management of new products and systems. Similarly, the cluster has a significant focus on research and capacity building to support SMEs."*

It's OWL research projects focus not only on product innovation itself, but also the development, deployment, maintenance, and life cycle management of new products and systems. Similarly, the cluster has a significant focus on research and capacity building to support SMEs. Its technology platform serves as a basis for dissemination, with transfer projects making technologies and methods developed by the cluster available to SMEs. It has seven industry support initiatives to support SME capabilities, including strategic foresight, education/training, internationalisation, start-ups, market orientation, acceptance and prevention of piracy.

Interestingly, significant efforts within It's OWL's projects are focused on developing ICT-based applications (such as self-optimisation and automation) for 'traditional' industries such as industrial laundry operations, furniture and white goods. Research projects on industrial laundries, for example, aim to increase the productivity of laundries and reduce consumption of energy, water and detergent by around 50% by developing self-optimisation methods and intelligent gripper robots (It's OWL, 2016).

5.7 | Cross-Ministerial Strategic Innovation Promotion Program (Japan)

The Cross-Ministerial Strategic Innovation Promotion Programme (SIP) is a national project for science, technology and innovation, led by Japan's Council for Science, Technology and Innovation (CSTI) (CSTI, 2015a). The programme focuses on 10 themes that have been designed to revitalise the Japanese society and economy, including some manufacturing-related themes aimed at boosting Japan's global industrial standing.

Each of these themes is assigned a director responsible for end-to-end research and development and liaison between appropriate government, industry and academic organisations as needed, managing their programmes from a cross-ministerial perspective. An advisory body formed by executive members of the CSTI provides counsel and expert assessment (CSTI, 2015).

Other features of the SIP programme include (CSTI, 2015):

- CSTI selects projects that directly address social needs and offer competitive advantages to Japanese industry
- Initiatives are cross-ministerial
- Initiatives promote end-to-end research development, from basic research to practical application and commercialisation
- Intellectual property rights are managed in a way that facilitates exploitation by Japanese corporations

One of the 10 themes identified by the SIP programme is Innovative design/manufacturing technologies, which focuses on improving digital linkages between upstream R&D activities and downstream product and production process design to (a) accelerate the scaling-up of new technologies and (b) achieve superior levels of customer satisfaction (CSTI, 2015).

This theme emphasises the use of digital manufacturing technologies to minimise time and costs for R&D and production, as well as opportunities to utilise digitalisation (internet-of-things and

> ***"The SIP programme theme 'Innovative Design/Manufacturing Technologies' focuses on improving digital linkages between R&D activities and product and production process design to (a) accelerate the scaling-up of new technologies and (b) achieve superior levels of customer satisfaction."***

smart factories) to respond to customer needs quicker. Such efforts are expected to increase the ability of firms to understand customer requirements and therefore manufacture products that provide superior levels of customer satisfaction. This philosophy to exceed customer expectations is referred to by the initiative as ‘delight manufacturing’ (Sasaki, 2015).

Example research projects funded by the SIP Programme theme Innovative Design/Manufacturing Technologies include production technologies for non-conventional geometries and the application of digital tools (such as the ones discussed in this report) to the development of new prototyping systems that could accelerate the scaling-up of products from R&D and design to production (Sasaki, 2015).

5.8 | Concluding observations

The case studies discussed in this section illustrate increasing emphasis in many governments around the world on the interplay between manufacturing, innovation, and economic growth. Unsurprisingly, policy approaches across countries vary, reflecting local scientific and industrial strengths as well as particular policy priorities.

However, there is common recognition that firms can capture value from advanced manufacturing in diverse ways. To illustrate this point, this section reviewed examples in selected countries addressing different types of challenges and opportunities across four advanced manufacturing dimensions: product, process, supply chain and customer demand. Differences in emphasis are discussed below:

- The UK’s HVM Catapult network and the Manufacturing USA institutes, for example, place particular emphasis on scale-up of new production technologies, but also pay attention to supply chain development and technician training. China’s National Manufacturing Innovation Centres seem to be adopting a similar focus.
- Germany’s Integrative Production Technology for High-Wage Countries Cluster of Excellence also has a strong process innovation focus, but with particular emphasis on developing production technologies (individualised, virtual, integrated technology and self-optimising production systems) that can allow manufacturing firms to remain competitive in high-wage economies.
- Germany’s It’s OWL initiative, one of the most high-profile efforts under the Industry 4.0 umbrella, has a strong focus on product development, particularly through the development of digital applications for new advanced manufacturing solutions for application in regional industries.
- Japan’s SIP theme Innovative Design/Manufacturing Technologies focuses on developing digital links between R&D, design and product, with particular emphasis on helping manufacturers develop features in products and services that ensure superior levels of customer satisfaction.

The variety of innovation functions addressed by recent advanced manufacturing programmes is also illustrated in the case studies presented in this section. While many of them have a core R&D component, they have also adopted additional functions including the provision of access to facilities, advanced training, and support for new product development.

It is hoped that the themes and examples presented here will provide practical insights to inform future advanced manufacturing research and innovation policies, initiatives and programmes.

6 | Conclusions and policy implications

OVERVIEW OF THIS SECTION

This section discusses the following concluding observations and policy implications:

- **The way policy-makers analyse manufacturing needs to be updated to reflect the increasing complexity of modern industries**
  New sources of data and analytical approaches are required to better understand challenges and opportunities in advanced manufacturing and the potential role of policies to support it. One promising approach is to redefine sectors as value networks.
- **Interpreting manufacturing as a cross cutting theme can help reveal the linkages between science, technology and innovation (STI) policies, and industrial strategies**
  Analysing manufacturing themes across industries and technologies can provide policy insights that cannot be fully revealed by analysing individual technologies or sectors, such as the potential to generate productive employment from science and research investments, mechanisms to support technology diffusion among SMEs and sustainability trade-offs.
- **Value capture in manufacturing goes beyond product development**
  While policy has traditionally focused on product technology development, there are opportunities to capture value beyond the product across the below four perspectives:
    - *Product innovation* – competing on speed of new technology development
    - *Process innovation* – competing on product mix flexibility and factory productivity
    - *Supply chain* – competing on reconfigurable supply chain capabilities
    - *Customer demand* – competing on superior knowledge of demand and higher levels of customer satisfaction
- **Impactful manufacturing research and innovation policy portfolios go beyond R&D**
  It is increasingly recognised internationally that capturing value from advanced manufacturing innovation requires more than funding basic R&D. Policy challenges might also include: promoting commercialisation by business and technology adoption by SMEs, developing appropriate technical standards, supporting specialist training programmes and fostering regional supply chains.
- **The race to value capture in advanced manufacturing is a race for scale-up and speed-to-manufacturing**
  The capability to rapidly scale-up emerging technologies from R&D prototypes into manufacturing may become the critical factors for capturing high-value from manufacturing-based industries. Policies, programmes and institutions that facilitate close interaction and sharing of insights between laboratory-based researchers, manufacturing engineers, equipment manufacturers and user industries will be essential.
- **Advanced manufacturing skills are becoming a critical factor for industrial competitiveness**
  There is evidence that skill shortages and gaps are already hampering growth in advanced manufacturing-based industries such as composites and biomanufacturing. It is being reported in a number of countries that it is already a challenge to attract and develop more sophisticated and multidisciplinary skills in the workforce. However, contrary to a perception held in some segments of society, the insights offered in this report show that manufacturing-based industries provide some of the newest and most exciting career opportunities.

The way policy-makers analyse manufacturing needs to be updated to reflect the increasing complexity of modern industries

The boundaries of manufacturing as an economic activity are increasingly blurry and advanced manufacturing is, in fact, inherently multi-dimensional. Modern manufacturing systems involve complex interdependencies distributed across a range of industries, technologies, subsystems and components.

As such, conventional sources of data based on traditional industrial sectors and academic discipline boundaries cannot provide policy-makers with a full understanding of the current complexity, and future challenges and opportunities. As software and services become ever more integrated into products, a number of unmeasurable sectors, such as embedded software and the app economy, are simply not monitored.

Instead of more complex statistical analyses based on the same traditional sectoral and technological boundaries, new approaches are necessary to more accurately represent the way in which modern economic activities are organised. In the USA, for example, calls are being made for novel approaches to better understand economic activity through the modelling of ‘value networks’ (NAE, 2015). In Japan, significant efforts are made to incorporate survey data systematically in the policy process (see, for example, METI, 2015).

In this context, the value of sophisticated insights and granular data about industries and technologies being incorporated into policy processes is becoming more evident (see, for example: CRDS, 2015; Foresight, 2013). Similarly, the potential contribution of policy units, research institutes and think tanks needs to be revisited.

Interpreting manufacturing as a cross cutting theme can help reveal the linkages between science, technology and innovation (STI) policies and industrial strategies

A more sophisticated appreciation of industrial and technological interdependencies requires that people in different but interdependent policy areas, including science, technology and innovation policy, communicate better. Policy initiatives in these areas may only achieve the expected results if appropriately aligned. Investments in technology development, for example, might only achieve their intended impact if they take into account the potential industrial applications they might have an effect on, and the ability of domestic firms to absorb that knowledge.

Similarly, programmes focused on particular sectors such as aerospace and automotive need to account for trends in technologies that are capturing an increased share of value added within those industries, such as advanced materials and artificial intelligence. They also need to account for developments in closely coupled sectors such as electronics and advanced machinery.

In this context, the potential of manufacturing as a cross-cutting theme with the potential to bring various policy areas together is increasingly relevant. Asking common manufacturing questions across industries and technologies can provide insights into issues (challenges, opportunities, strengths and weaknesses), which are not fully revealed by analysing individual technologies or particular industry sectors independently.

This approach can provide a better understanding of issues of critical importance to national industrial competitiveness: linkages and interdependences between manufacturing and innovation, the potential to generate manufacturing employment from science and research investments, potential mechanisms to support technology diffusion among SMEs, and sustainability trade-offs. Countries like South Korea and Japan, for example, consider manufacturing as a cross-sectoral theme and have established institutional set-ups that allow the countries to systematically capture common manufacturing issues across industries and technologies.

Value capture in manufacturing goes beyond product development

Understanding the way firms capture value from modern manufacturing is essential to better appreciate the potential impact of manufacturing research and innovation. While the policy focus has traditionally been on product technology development, considering four basic advanced manufacturing perspectives can help to better appreciate the variety of ways in which firms can capture value from advanced manufacturing:

- **Product innovation** – firms can capture value by competing on the speed to technology development. This includes the development of products with improved functionalities, performance and reliability through the application of, for example, advances in science and engineering (e.g. nanotechnology, chemistry and biology)
- **Process innovation** – firms can capture value by competing on product mix flexibility and factory productivity. This may include the development production technologies capable of achieving more complex shapes and ever tighter process tolerances and development of hybrid production technologies and systems able to deliver individualised products at mass production prices (to achieve both economies of scale and scope)
- **Supply chain** – firms can capture value by competing on reconfigurable supply capabilities. This includes the ability to upgrade and diversify to supply new materials and components faster and more efficiently, for both current as well as next-generation products
- **Customer demand** – firms can capture value by exploiting a superior knowledge of customer demand and achieving higher levels of customer satisfaction. This may include creating stronger links between research, design and delivery, and a more intensive use of big data analytics to better appreciate and foresee changing patterns of customer wants and needs

As illustrated by the Industry 4.0 concept, cross-cutting technologies such as ICT can create new sources of competitiveness across all perspectives outlined above. Such technologies can not only help develop more sophisticated products, but also better production technologies, more efficient and responsive supply chains, and a better understanding of customer needs and wants.

Impactful manufacturing research and innovation policy portfolios go beyond R&D

Designing impactful policy portfolios requires a more systemic understanding of innovation. Yet the debate in academia and outside has largely focused on knowledge generation (primarily through R&D funding programmes). Relatively little attention has been paid to additional roles that public institutions could provide to support knowledge diffusion and application, which are critical to ensuring efficient translation into industry.

It is recognised in many recent national industrial and innovation strategies, however, that a wider range of innovation activities is required to support the emergence of new industries and the upgrading of established ones. As such, the policy challenge to support advanced manufacturing innovation involves not only funding basic R&D, but also supporting the scale-up of emerging technologies, promoting commercialisation by business and adoption by SMEs, developing appropriate technical standards, ensuring mechanisms for training of advanced manufacturing professionals, and even promoting regional development.

A broader conception of innovation functions is evident in recent initiatives reviewed in this report. For example, the HVM Catapult centres in the UK and the Manufacturing USA institutes in the USA, place emphasis on the opportunities of using R&D competencies to support SME growth and supply chain development and carry out specialised technician training.

The race to capture value in advanced manufacturing is a race for scale-up and speed-to-manufacturing

The 20th century model, where technological innovation is driven by a small number of countries with leading research universities and major R&D-intensive corporations dominating their supply chains, is rapidly disappearing. In the new global context, the capability to rapidly scale-up emerging technologies from R&D prototypes into manufacturing, and the ability to coordinate the complex manufacturing systems into which these technologies diffuse, may become the critical factors for capturing high-value from manufacturing-based industries (O'Sullivan, 2016).

All too often, progress in advancing the functionality of new application technologies and efforts to enhance the functionality of novel production technologies are often carried out in isolation from each other. For many promising emerging technologies, product R&D and complementary production technology R&D needs to happen hand-in-hand. Policies, programmes and institutions that facilitate close interaction and sharing of insights between laboratory-based researchers, manufacturing engineers, equipment manufacturers and user industries will be essential.

Advanced manufacturing skills are becoming a critical factor for industrial competitiveness

Skills are given central importance in national manufacturing and innovation policy agendas around the world. There is a broad common perception in the countries reviewed in this report that skill shortages (related to insufficient supply of certain skills) and skill gaps (associated with the hiring of under-skilled workers) represent some of the most serious threats to current and future national competitiveness. There is evidence that growth is already being hampered by skill gaps in emerging areas such as biomanufacturing and composite manufacturing in the aerospace and automotive industries (López-Gómez et al, 2015).

Paradoxically, while firms across many countries struggle to hire the right employees, unemployment is an increasingly important concern. In some advanced economies, these mismatches are exacerbated by a rapidly ageing population and the deterioration of the image of manufacturing among the general public.

Contrary to a perception held in some segments of society, however, the insights offered in this report show that advanced manufacturing-based industries provide some of the newest and most exciting career opportunities.

Advanced manufacturing requires workers with new multidisciplinary competencies, combining mechanics, electronics and software knowledge and skills. New roles on information management are emerging across the value chain and proficiency in new computerised modelling and simulation tools and data analytics is increasingly required. Complex system thinking and cyber-security competencies are becoming more important as processes and machines become increasingly interdependent. Proficiency in methodologies for real-time decision making are becoming more important, as it is the knowledge of international standards.

More generally, some of the most radical innovations emerging today will only deliver their full benefits to society when technicians, engineers and managers are able to embed them into new products, processes and manufacturing systems operating at full industrial scale.

Glossary

Advanced Manufacturing: use of innovative technologies, such as automation, computation, software, sensing and networking, to create existing and new products.

Artificial Intelligence (AI): the simulation of human intelligence processes by machines. These processes include learning (the acquisition of information and rules for using the information), reasoning (using the rules to reach approximate or definite conclusions), and self-correction. AI is being used for design and control of flexible manufacturing systems.

Big data: analysis of big data requires new software tools and database systems to deal with large, unstructured datasets; and refining analytical tools so that they can process vast quantities of data in near-real time.

Cloud Computing: a broad umbrella term that initially referred to storing, accessing and sharing data through the internet using an off-site service provider. Cloud computing now allows manufacturers to connect machines, materials, and people in real time and across their supply chains.

Cyber-physical systems (CPS): smart networked systems with embedded sensors, processors and actuators, designed to sense and interact with the physical world (including human users) and support real-time, guaranteed performance in applications. Examples include smart grid, autonomous automobile systems, medical monitoring, process control systems and robotics systems.

Digitalisation of Manufacturing: digitally-enabled, data-driven intelligent systems for industrial applications such as machinery, assembly, packaging, material handling and warehouse management. It includes broad areas such as smart factories, rapid prototyping., distributed manufacturing, supply chain optimisation or delivering complex services with real-time asset monitoring.

Fourth Industrial Revolution: the next industrial era where a fusion of technologies that are blending the lines between physical, digital, and biological spheres, for example smart factories where materials, people and machines seamlessly collaborate to drive productivity and efficiency.

Internet-of-Things (IoT): network of physical objects (devices, vehicles, buildings, equipment, etc) embedded with electronics, software, sensors, and connected to internet, enabling objects to collect and exchange data.

Machine Learning (ML): a type of artificial intelligence that provides machine computers with the ability to learn without being explicitly programmed. In manufacturing, machine learning can predict equipment failure, lower consumption rates and improve productivity.

Megatrends: major (non-sector-specific) global trends shaping the future of manufacturing with the potential to redefine sources of industrial competitiveness. With their pervasive effects on global industry, ‘megatrends’ drive competing agendas as to what needs to be produced, where and how.

Pilot (Production) Lines: a line of production set-up to test new methods, processes and systems.

Reshoring: a company decision to relocate activities back to the home country regardless of the ownership of the activities relocated.

Technology Readiness Level (TRL): a method of assessing technology maturity based on a scale from 1 to 9, where 1 stands for basic technology research and 9 for technology applied in a commercial real-world application.

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