The Next Production Revolution
Implications for Governments and Business

Chapter 1

The next production revolution: Key issues and policy proposals

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This chapter contextualises the overall report and distils the main findings and policy ideas set out in the chapters on digital technologies, industrial biotechnology, nanotechnology, 3D printing and new materials. Also summarised and commented on are the main messages from the chapters addressing the following cross-cutting themes: institutions for technology diffusion, public acceptance and emerging production technologies, using foresight processes, emerging manufacturing research and development (R&D) priorities and policies, advanced manufacturing institutes in the United States, and how the next production revolution is unfolding in the People's Republic of China. This introductory chapter also describes a number of additional policy considerations and provides a wider substantive background to the study, in particular by examining the following: the relationship between productivity and the technologies of the next production revolution; work, automation and new production technologies; policies for science and R&D; challenges for education and training; selected labour market developments; geography-specific policies; emerging challenges for intellectual property systems; the need for long-term policy thinking; and possible implications for global value chains. This chapter also points to themes which require further assessment.

Introduction

The next production revolution will occur because of a confluence of technologies. These range from a variety of digital technologies (e.g. 3D printing, Internet of Things [IoT], advanced robotics) to new materials (e.g. bio- or nano-based), to new processes (e.g. data-driven production, artificial intelligence [AI] or synthetic biology). Some of these technologies are already used in production. Others will be available in the near future. As these technologies transform production they will have far-reaching consequences for productivity, employment, skills, income distribution, trade, well-being and the environment. All of these technologies are evolving rapidly. The more governments understand how production could develop, the better placed they will be to help companies, economies and societies achieve the benefits and address the challenges.

A range of policy, institutional, technological and broader conditions (or megatrends) will shape the future of production (OECD, 2015a). For example, environmental conditions and the growing scarcity of some raw materials will increase pressure for materials-, water- and energy-efficient production. The continued accumulation of human capital in OECD countries, which has trended upwards for decades, could favour production of increasingly knowledge-intensive goods. And demographics will influence which products are most demanded by consumers and where production is located, while many other factors could also influence location, from political instability in some parts of the world to weather patterns.

This report has a technological focus

This report examines the economic and policy ramifications of a set of technologies likely to be important for production over the near term (to around 2030). The focus on technologies affords the opportunity for thinking about technology-related themes and policies, which are many. A concentration on technological features of future production also permits tractability. Various high-profile studies have recently addressed the digitalisation of production, a phenomenon referred to with terms such as "Industry 4.0" and "advanced manufacturing" (Box 1.1). This report takes a wider view, examining important technologies which are not only digital, such as industrial biotechnology and aspects of production beyond manufacturing.

A technological perspective also introduces an appreciation of the importance of some fields of government action which are not always central in micro-economic analyses of productivity and growth. Cases in point, discussed in this report, include: decisions on the composition of public support for manufacturing R&D and how allocation choices might increase impact and efficiency; the design and resourcing of, and performance metrics used for, institutions that diffuse technology; the operation of public-private research partnerships; the benefits of sector-specific understanding of technical change; how the increasing complexity and digital foundation of many production systems creates new interdependencies between firms, technologies and a variety of institutions (such as providers of resources for supercomputing); the evolution of technology-specific skill needs; the processes that governments use to prepare for the future; and how policy can shape public attitudes to technology, which can itself affect the course of technology adoption. Insights on these and other policy issues can complement standard analyses of firms and markets. Furthermore, accounts of past episodes of technological change in production, as sketched in a subsection of this chapter, can help to inform responses to today's technological disruptions.

Box 1.1. **Industry 4.0 and the next production revolution**

The term "Industry 4.0", or the fourth industrial revolution, refers to the use in industrial production of recent, and often interconnected, digital technologies that enable new and more efficient processes, and which in some cases yield new goods and services. The associated technologies are many, from developments in machine learning and data science, which permit increasingly autonomous and intelligent systems, to low-cost sensors which underpin the IoT, to new control devices that make second-generation industrial robotics possible.

In using the term Industry 4.0, the contrast is made with three previous industrial revolutions. These three revolutions can only be dated approximately. They are: i) the advent of steam-powered mechanical production equipment (1780s, or thereabouts); ii) electrically powered mass production (1870s); and iii) electronically based, automated production (1960s) (although with many differences compared to the electronics of Industry 4.0, e.g. in terms of cost, size, computational power, intelligence, interconnectivity, and integration with material objects).[1]

1. Ezell (2016) points out that there are grounds for describing the current transformation as "Industry 5.0", because much commentary overlooks the emergence of science-based industries, including electronics and chemicals, and the major process improvements they bought, in the decades after the Second World War. This transformation is often placed together with the phase of electrically powered transformation seen in the late 1800s.

Many technological changes will affect production over the next 10 to 15 years. The technological possibilities of production are continuously expanding, with technologies complementing and amplifying each other's potential in combinatorial ways. Today, for example, advances in software and data science help to develop new materials. In turn, new materials might replace silicon semiconductors with better-performing substrates, allowing more powerful software applications. This combinatorial feature of technology means that foresight is always tenuous. Predictions of technological timelines – when certain milestones will be reached – are frequently inaccurate (Armstrong, Sotala and ÓhĖigeartaigh, 2014). And the scope of change is often surprising. Just a few years ago, few would have foreseen that smartphones would disrupt, and in some cases bring to an end, a wide variety of products and industries, from notebook computers to personal organisers, to niche industries making musical metronomes and hand-held magnifying glasses (functions now available through mobile applications). As this book shows, many potentially disruptive production technologies are on the horizon, but the scope of the disruption is uncertain.

National initiatives for advanced manufacturing have proliferated in recent years. Germany's Industry 4.0 initiative ("Plattform Industrie 4.0"), the National Network for Manufacturing Innovation in the United States, Japan's Robot Strategy, the People's Republic of China's (hereafter "China") Made in China 2025 and Internet Plus initiatives are just some examples. As Chapters 9 and 10 describe, many countries have prepared national manufacturing foresight studies and strategies, as well as in-depth roadmaps, for priority manufacturing technologies. And manufacturing has grown as a theme in recent national research and innovation strategies.

Governments have many motivations for interest in how production is evolving. The effect of technological change on employment and earnings inequality is drawing increased attention from academics, policy makers and the public, and fears of technology-induced unemployment have gained traction worldwide. The need to raise labour productivity in ageing OECD countries forces a focus on technology and innovation, the principal determinants of growth in productivity and living standards. Many policy makers are also concerned by the consequences of unpreparedness in a context of rapid but hard-to-foresee technological change. As the German Chancellor Angela Merkel asserted in Davos, in 2015, “I want our strong German economy to be able to cope with the merger of the real economy and the digital economy, otherwise we will lose out to the competition.” (Merkel, 2015). As this report shows, unpreparedness might take various forms – from skills and infrastructure deficits to regulatory shortcomings – and have numerous consequences. As a corollary to the risk of machine-driven labour displacement, automation might also undermine labour-cost advantages on which many emerging economies rely. A precursor of this possibility could be the decision of Foxconn to invest massively in robots.[1]

The structure of the report and the scope of this chapter

This chapter contextualises and summarises the overall report. The report’s chapters are divided into two blocks. The first block, of five chapters, focuses on individual technologies: digital technologies, industrial biotechnology, nanotechnology, 3D printing and new materials. A second block of chapters addresses cross-cutting themes, namely: institutions for technology diffusion, public acceptance and emerging production technologies, using foresight processes, emerging manufacturing R&D priorities and policies, advanced manufacturing institutes in the United States, and how the next production revolution is unfolding in China.

This introductory chapter also describes a number of additional policy considerations and provides wider substantive background to the study. Accordingly, the remainder of this chapter includes sections on: the relationship between productivity and the technologies of the next production revolution; work, automation and new production technologies; policies for science and R&D; challenges for education and training; selected labour market developments; geography-specific policies; emerging challenges for intellectual property systems; the need for long-term policy thinking; and possible implications for global value chains. The conclusion points to themes which require further assessment.

Productivity and the technologies of the next production revolution

For a number of reasons, the possible productivity effects of new production technologies are of great current policy interest. Research has established a fundamental relationship between innovation and long-term productivity. Today, raising rates of economic growth is a priority for most OECD governments. Sluggish macroeconomic conditions in many OECD countries, weak labour markets and burgeoning public debt have all added urgency to the search for growth. Over the longer term, the decline in the working-age population, combined with environmental constraints, means that the future of growth in OECD countries will increasingly depend on productivity-raising innovation.

However, many OECD countries have experienced faltering productivity growth in recent years. Some high-profile commentators claim that slower productivity reflects a general innovation hiatus. These voices come from academia, notably Gordon (2012), and from industry, such as Peter Thiel, the founding chief executive officer (CEO) of PayPal. Some of the arguments made by techno-pessimists cite obstacles to productivity which are particularly relevant to the United States, such as growing inequality and consumer and government debt. But other arguments are more global, particularly the claim that innovation will slow because the cost of innovation rises as technology advances (Jones, 2012). In contrast, techno-optimists variously argue that new digital and other technologies will raise productivity (Brynjolfsson and McAfee, 2014), and that economic history provides reasons to think that technological progress could even accelerate (Mokyr, 2014). A further argument of techno-optimists is that official measures of economic growth understate progress, because they poorly capture many of the benefits of new goods and services. For example, national statistical offices usually collect no information on the use of mobile applications, or online tax preparation, or business spending on databases (Mandel, 2012), while the consumer surplus created by hundreds of new digital products is absent from official data.

In recent years the OECD has closely studied the drivers of economic productivity. Much of this work has examined the effects of framework policies, innovation and enterprise demography (e.g. OECD [2015c], Andrews, Criscuolo and Menon [2014] and Andrews, Criscuolo and Gal [2015]). This section does not reprise that work. Rather, the following paragraphs consider the current and potential productivity effects of the technologies analysed in this report.

Emerging technologies affect productivity through many channels

Emerging production technologies can affect productivity through many routes. For example:

- The combination of new sensors, control devices, data analytics, cloud computing and the IoT is enabling increasingly intelligent and autonomous machines and systems.
- Intelligent systems can almost entirely eliminate errors in some production processes. Among other reasons, this is because sensors allow every item to be monitored, rather than having to test for errors in samples drawn from batches. Machine downtime and repair costs can be greatly reduced when intelligent systems predict maintenance needs. Savings can be had if industrial products can be simulated before being made, and if industrial processes can be simulated before being implemented. Data-driven supply chains greatly speed the time to deliver orders. And digital technologies can allow production to be set to meet actual rather than projected demand, reducing the need to hold inventories and lowering failure rates for new product launches.
- By being faster, stronger, more precise and consistent than workers, robots have vastly raised productivity on assembly lines in the automotive industry. They will do so again in an expanding range of sectors and processes as industrial robotics advances.
- The mix of industrial biotechnology with state-of-the-art chemistry can increase the efficiency of bioprocesses (most biological processes have low yields).
- By printing already-assembled mechanisms, 3D printing could remove the need for assembly in some stages of production.
- Progress in materials science and computation will permit a simulation-driven approach to developing new materials. This will reduce time and cost because, in searching for materials with desired qualities, companies will be able to avoid the repetitive analysis of candidate materials and simply build the desired qualities into materials from the start.

- Nanotechnology can make plastics electrically conductive. In the automotive industry this can remove the need for a separate spray painting process for plastics, reducing costs by USD 100 per vehicle.

Synergies among technologies will also aid productivity. For example, so-called "generative" software can mimic evolutionary processes and create industrial designs which optimise product weight and strength in ways not evident to human designers. It does this by evolving multiple variants on an initial design, eliminating the least fit designs in successive stages, while further evolving the better fits. In this way, the Dreamcatcher software designed the chassis of the world's fastest motorbike, the Lightning Electric Motorcycle (Kinkead, 2014). Such software also created an aircraft bulwark partition almost 50% lighter than previous models (Autodesk, 2016). However, generative design software sometimes yields shapes that can only be manufactured with 3D printing. A combination of the two technologies is required. In a similar example of synergy, advances in simulation will combine with advances in augmented reality to permit maintenance engineers to see real-time projections, on visors or glasses, of the inner workings of machines.

Box 1.2. **How large are the productivity effects?**

Evidence on productivity impacts from new production technologies comes mainly from firm and technology-specific studies. A sample of these studies is given here. These studies suggest sizeable potential productivity impacts. However, by way of caveat, the studies follow a variety of methodological approaches, and often report results from just a few, early adopting technology users:

- In the United States, output and productivity in firms that adopt data-driven decision making are 5% to 6% higher than expected given those firms' other investments in information and communication technology (ICT) (Brynjolfsson, Hitt and Kim, 2011).
- Improving data quality and access by 10% – presenting data more concisely and consistently across platforms and allowing them to be more easily manipulated – is associated with a 14% increase in labour productivity on average, but with significant cross-industry variations (Barua, Mani and Mukherjee, 2013).
- The IoT reduces costs among industrial adopters by 18% on average (Vodafone, 2015).
- Autonomous mine haulage trucks could in some cases increase output by 15-20%, lower fuel consumption by 10% to 15% and reduce maintenance costs by 8% (Citigroup-Oxford Martin School, 2015).
- Autonomous drill rigs can increase productivity by 30% to 60% (Citigroup-Oxford Martin School, 2015).
- Warehouses equipped with robots made by Kiva Systems can handle four times as many orders as un-automated warehouses (Rotman, 2013).
- Google data centres use approximately 0.01% of the world's electricity (Koomey, 2011). In July 2016 it was reported that DeepMind – a leader in AI – used AI to optimise cooling of data centres, cutting energy consumption by up to 40% and significantly reducing costs.[1]
- A 1% increase in maintenance efficiency in the aviation industry, brought about by the industrial Internet, could save commercial airlines globally around USD 2 billion per year (Evans and Anninziata, 2012).

1. See *https://deepmind.com/blog/deepmind-ai-reduces-google-data-centre-cooling-bill-40/*.

The technologies considered in this report have more to contribute to productivity than they currently do. Often, their use predominates in larger firms. This is the case even for technologies which should be accessible for smaller firms, such as low-cost robots. And even in larger firms, many potential applications are underused. Unexploited opportunities exist throughout industry. For example, robotics could improve logistics and reduce the price of food and other goods by several percent (CCA/CRA, 2009). Manufacturers see unmet opportunities for automation in skilled and less-skilled fields, from manufacturing parts, to machine loading, packaging, palletisation and assembly (Rigby, 2015).

It could take considerable time for the productivity gains from new technologies to be realised. The past has seen unrealistic enthusiasm regarding timescales for the delivery of some industrial technologies. In some cases, as with nanotechnology, this reflects miscalculation of the technical challenges. And many technologies, such as big data and the IoT, have developed in a wave-like pattern, with periods of rapid inventive activity coming after periods of slower activity and vice versa (OECD, 2015b). In terms of adoption, advanced ICTs remain below potential. Cloud computing, for example, was first commercialised in the 1990s, but has still only been adopted by less than one in four businesses in OECD countries. By one estimate "the full shift to Industry 4.0 could take 20 years" (Lorentz et al., 2015). The mere availability of a technology is not sufficient for its uptake and successful use. Realising the benefits of a technology often requires that it be bundled with investments in complementary intangible assets, such as new skills and organisational forms, and that better adapted business models are invented that channel income to innovators.

Work, automation and the new technologies of production

Among the general public, senior policy figures and business leaders, growing concerns have recently been voiced regarding the employment implications of digital technologies. For example, in 2014 the former Secretary of the United States Treasury, Lawrence Summers, argued that a limited availability of jobs will be the defining upcoming economic challenge (Summers, 2014). In a much-cited study, Frey and Osborne (2013) concluded that about 47% of total employment in the United States is at risk of computerisation (over a number of decades). A spate of recent books has gone even further, warning of the eventual redundancy of most human labour (e.g. Ford, 2015; Brynjolfsson and McAfee, 2014). Concern also exists that the digital economy is not creating the large number of jobs created by leading industries of the past. Lin (2011), for example, shows that 8.2% of workers in the United States were employed in new types of jobs in 1990. But this figure fell to 4.4% by 2000. And Berger and Frey (2015) estimate that less than 0.5% of workers in the United States are now employed in technology-related industries created in the 2000s. A recent survey of technology experts in the United States found that 48% were concerned that digital technologies would lead to widespread unemployment (PEW, 2014). Fears also exist that digital technologies could alter the nature of labour markets – e.g. through the growth of a crowd-sourced workforce – to the detriment of some workers.

Concerns over technology-based unemployment have a long history. Even before the Luddite protests against the mechanisation of textiles manufacture in early nineteenth-century England, many production technologies have raised fears of labour market disruption. The term "technological unemployment" was coined by John Maynard Keynes in 1930 (Keynes, 2009). In 1961, in the United States, the Kennedy Administration created an Office of Automation and Manpower, citing "the major domestic challenge of the Sixties: to maintain full employment at a time when automation, of course, is replacing men" (quoted in Miller and Atkinson, 2013). More recently, workers polled in the United States in the 1970s and 1980s were constantly concerned about automation (Miller and Atkinson, 2013). Most of these fears have turned out to be unjustified. Nevertheless, many commentators argue that aspects of today's digital technology give such fears a new foundation.

Progress in computing is leading to novel machine capabilities and an increased scope and rate of automation. Since the period of manual computing, and depending on the metrics used, the cost of computer calculation has fallen 1.7 trillion- to 76 trillion-fold. Most of this decline has happened since 1980 (Nordhaus, 2007). Such progress permits the development of some machine functionalities that rival human performance, even in tasks where humans were long thought to possess a permanent cognitive advantage over machines (Elliott, 2014). For example, researchers recently reported advances in AI that surpass human capabilities in a set of vision-related tasks (Markoff, 2015a).

The routine tasks of most operatives in manufacturing are now automated in OECD countries. Cargo-handling vehicles and forklift trucks are increasingly computerised. Many semi-autonomous warehouses are populated by fast and dexterous robots. Complex aspects of the work of software engineers can be performed by algorithms (Hoos, 2012). A version of IBM's Watson computer can act as a customer service agent (Rotman, 2013). The Quill programme writes business and analytic reports and Automated Insights can draft text from spreadsheets. Computer-based managers are being trialled. These allocate work and schedules, with the experience well received by teams of workers to date (Lorentz et al., 2015). Recent software can interpret some human emotion better than humans, presaging new forms of machine-human interaction (Khatchadourian, 2015). And autonomous vehicles might soon substitute for tasks performed by many commercial drivers.

So-called "routine" tasks are tasks more easily defined in computer code. Non-routine tasks are harder to specify in code. Routine and non-routine tasks can be manual or cognitive.[2] In recent decades, the share of employment in high- and low-wage jobs has increased in developed countries' labour markets, while the share of employment in middle-wage jobs has fallen. This polarisation has been linked to the falling share of employment in occupations that involve many routine tasks (Goos and Manning, 2007; Acemoglu, 2002). Because manual tasks in many services occupations are less easily described in code, automation has also contributed to a shift in employment from middle-income manufacturing to low-income services (Autor and Dorn, 2013).

The labour market effects of technology have been highlighted by the crisis. Apprehension about technology's effects on employment tends to grow during economic crises (Mokyr, Vickers and Ziebarth, 2015). This may in part account for the recent upswing of technology-related anxiety. Some of the alarm about technology and jobs might also reflect cognitive biases: novel technological developments attract disproportionate attention; to report on job losses is easier than to report on job gains; and, it is hard to discern the nature of future jobs. But the recent recession appears to have accelerated the displacement of workers by computerised systems (Jaimovich and Siu, 2012).

Technological development also creates jobs through a number of channels

Firms invest in new technologies to increase productivity (and to achieve other outcomes, such as regulatory compliance and greater safety). In a given firm, this increased productivity can lower, raise, or leave unchanged the number of workers. The actual outcome depends on the price elasticity of demand for the firm's output. If demand is sensitive to changes in price, a small decline in the price of the firm's output could lead to an increase in the firm's workforce (Autor, 2015).

A technology-driven increase in productivity benefits the economy through one or more of the following channels: lower prices of output, higher workers' wages, or higher profits. Lower output prices raise the real incomes of consumers. This can increase demand for other goods or services. And higher workers' wages may raise demand and job creation in other markets. Higher profits are distributed to shareholders, who may spend all or part of this new income, adding to aggregate demand. And increases in savings, among shareholders and workers, eventually lowers interest rates and raises investment, creating jobs.

In this relationship between technology and jobs, key issues concern the quantitative balance between jobs lost and jobs gained; the characteristics of the jobs lost and the characteristics of those created; and the duration and efficiency of the labour market and other economic adjustment processes involved. These adjustment processes are conditioned by the efficiency of institutions (such as financial services, that mediate between savings and investment), and a range of micro- and macroeconomic policies. General competitive equilibrium can be expected in the long term. But obstacles might exist in the short run. Profits, for example, might not be invested due to a lack of expected demand (and this lack of demand might in turn be partly attributable to high levels of profit, which dampen consumption).

Historical evidence is positive regarding the overall economic and labour market effects of technological change. To cite just a few country-level studies:

- Investments in ICT are estimated to have raised total labour demand in 19 OECD countries over the period 1990-2007 (but to have reduced it after 2007). ICT investments appear to have no effects on total labour demand in the long run. A permanent decrease in the cost of ICT capital reduces labour demand per unit of output, but increases output by the same proportion. This overall employment neutrality is accompanied, however, by a shift in employment from manufacturing to services (OECD, 2016a).
- In the short-run, employment might decrease following productivity-enhancing technology shocks, but it grows again over the medium term (Basu, Fernald and Kimball, 2006). Productivity-raising technology shocks reduce unemployment for several years (Trehan, 2003).
- From 1964 to 2013, against a background of accelerating automation, the United States economy created 74 million jobs (Levy and Murnane, 2013).
- In England and Wales, over one-and-a-half centuries, technological change has led to overall job creation (Stewart, Debapratim and Cole, 2014). This period saw a reduction in jobs requiring physical strength: 24% of all employment in 1871, to 8% in 2011. It also saw a shift to jobs requiring caring and empathy: 1% of all employment in 1871 to 12% in 2011. Routine jobs suffered most.

In firms and industries, the employment effects of technological change are also generally positive. Productivity-enhancing technology causes job losses in some cases and job gains in others (Miller and Atkinson, 2013). However, the number of firms and industries which experience employment growth exceeds the number in which employment contracts.[3]

But adjustment might be painful

The first industrial revolution eventually brought unprecedented improvements in living standards. But for many workers this revolution brought hardship. Indeed, the shift to higher average living standards took many decades, often longer than the typical working lifetime (Mokyr, Vickers and Ziebarth, 2015).

Hardship could affect many if labour displacement were to occur in a major sector, or in many sectors simultaneously. The technology of driverless vehicles is a frequently commented example of such potential displacement. Taken together, just over 3 million people work as commercial drivers in 15 European Union member states. Eliminating the need for drivers could create an exceptional labour market shock, although penetration of autonomous vehicles into the commercial fleet would take time. However, the likelihood of major simultaneous technological advances in many sectors is low (Miller and Atkinson, 2013). And in any given sector, the employment effects of new technology are not always straightforward. For example, full vehicle autonomy would probably substitute for some but not all of the tasks performed by drivers. In addition to the task of driving, for example, many delivery drivers interact with customers in ways that today's machines cannot (Markoff, 2015b).

The specific types of work brought by new technology have often been hard to predict. For example, after the introduction of the personal computer in the early 1980s, more than 1 500 new job titles appeared in the United States' labour market, from web designers to database administrators (Berger and Frey, 2014). New technologies can also affect employment in indirect and unexpected ways, hindering foresight. For example, Toyota has decided to put human workers back into manufacturing after realising that craftsmen also play a role in improving production processes, which robots currently do not (Markoff, 2015b). And, in future, as the safety of self-driving cars is demonstrated, the demand for work in auto-body repair shops could fall, as could the need for workers in insurance companies (Jain, O'Reilly and Silk, 2015).

Nor is it possible to precisely predict how new technologies might transform existing jobs. In banking it was long believed that automated teller machines (ATMs) would cancel the need for human tellers. ATMs were introduced in the 1970s. But between 1971 and 1997 the share of human tellers among all workers in US banking only declined modestly, from just under 21% to around 18% (Handel, 2012). Numerically, the major workforce change occurred in banks' back offices, e.g. with clerical jobs (Markoff, 2015b). However, the nature of the work performed by human tellers changed, coming to involve more skilled services (such as financial advice).[4]

While automation is advancing quickly, machine substitution for workers still has limits. Frey and Osborne (2013) identify three broad categories of ability in which computer-controlled equipment is unlikely to surpass workers in the near term: creative intelligence, social intelligence (as exercised for instance in caring professions), and perception and manipulation (as required for example in jobs dealing with unstructured or changing environments). Common sense, a hard-to-define attribute which is essential to most work, has also been exceedingly hard to replicate in machines (Davis and Marcus, 2015).

Policy makers need to monitor and prepare for adjustment processes

This section has highlighted historical evidence that productivity-raising technologies lead to labour market adjustments at higher levels of income. It has also underscored that such adjustment might be highly disruptive, although the precise pace and scale of inevitable future adjustments are unknown. It may be that, in the worst case, labour will be displaced on a scale and at a speed not seen before, that robots will make income distribution vastly more unequal than today, and that the market wages of the unskilled will fall below socially acceptable levels. Policy makers need to monitor and prepare for such possibilities.

Digital technologies and future production

In Chapter 2, Christian Reimsbach-Kounatze addresses the role of digital technologies in future production. Two trends make digital technologies transformational for production: i) their falling cost, which has allowed wider diffusion; and ii) the combination of different ICTs, and their convergence with other technologies (thanks in particular to embedded software and the IoT).

Chapter 2 outlines the impacts and policy implications of key digital technologies, including big data, cloud computing and the IoT. The term "big data" refers to data characterised by their volume, velocity (the speed at which they are generated, accessed, processed and analysed) and variety (structured and unstructured). Big data promises to significantly improve products, processes, organisational methods and markets. Data-driven innovation will affect production and productivity across the economy, in manufacturing, services and agriculture.

As a number of chapters in this report show, many high-potential industrial applications of ICTs, such as autonomous machines and systems, and complex simulation, are computationally intensive. Especially for start-ups and small and medium-sized enterprises (SMEs), cloud computing has increased the availability and affordability of computing resources. But large variation exists across countries and firms – especially firms of different size – in the use of cloud computing.

The IoT is bringing radical changes. The IoT connects devices and objects to the Internet. It can improve process efficiencies, speed of decision making, consistency of delivery, customer service and predictability of costs (Vodafone, 2015). And thanks to new sensors and control devices, combined with big-data analysis and cloud computing, the IoT enables increasingly autonomous machines. Another notable effect of the IoT is to make industry more services-like. This is because manufacturers can provide customers with new pay-as-you-go services based on real-time monitoring of product use. Manufacturers of energy production equipment, for example, increasingly use sensor data to help customers optimise complex project planning.

Promoting investments in and use of ICTs and data: Main policy considerations

Governments aiming to promote the supply of key ICTs should consider supporting investments in R&D in enabling technologies such as big-data analytics, cloud and high-performance computing, and the IoT, as well as in security- and privacy-enhancing technologies. For example, through its 2014 national digital economy strategy, Canada has foreseen investment of CAD 15 million over three years to support leading-edge research in, and the commercialisation of, quantum technologies.

Promoting investments in and use of ICTs and data: Main policy considerations *(cont.)*

Governments should consider using demand-side policies to encourage investment in and adoption of key enabling ICTs, especially by SMEs. This can be done through activities such as awareness raising, training, mentoring and voucher schemes. Demand-side policies should also complement (existing) ICT supply-side policies. In Germany, for example, policies supporting investments in R&D related to industrial ICT applications, information technology (IT) security research, microelectronics and digital services, are complemented with demand-side policies such as awareness raising and training (e.g. through two big-data solution centres established in Berlin and Dresden).

Governments should encourage investment in data that have positive spillovers across industries and higher social than private value, while addressing the low appropriation of returns to data sharing. To address the low appropriation of returns to data sharing, governments should consider using a combination of intellectual property rights (IPRs), licences and alternative incentive mechanisms, such as data citations and data donation.

Governments should promote open standards, including in application programming interfaces (APIs) and data formats. Standards based on pro-competitive and technologically open reference models could boost data interoperability and reuse and digital services, and reduce technological lock-ins, while enhancing competition among service providers. Standards development at the international level is an important part of the United Kingdom's Information Economy Strategy.

Barriers to ICT diffusion, interoperability and standards should be lowered

A key observation in Chapter 2 is that many businesses, and in particular SMEs, lag in adopting ICTs. For example, the adoption of supply chain management, enterprise resource planning (ERP), and cloud computing applications by firms is still much below that of broadband networks or websites. But it is these advanced ICTs that enable digitalised industrial production.

An important aspect of interoperability for the IoT is identification and numbering policies. An issue that warrants special attention by governments and regulators is the liberalisation of access to international mobile subscriber identity (IMSI) numbers. IMSI numbers allow different sectors of the economy, such as car manufacturers and energy companies, to have access to SIM cards without being obliged to go through mobile operators. This would provide these sectors with more flexibility when selecting a specific mobile network and ease the deployment of the IoT across borders. The Netherlands was the first country to liberalise access to IMSI numbers.

Digital technologies also bring new risks and regulatory challenges. For example, data analytics permits new ways to make decisions that can raise productivity. But data-driven and AI-enabled decisions can also be mistaken. The risk of erroneous decisions raises questions of how to assign liability between decision makers, the providers of data and ICTs (including software). New ICTs could also raise serious concerns relating to privacy, consumer protection, competition and taxation. Existing regulatory frameworks may be ill-suited for some of the upcoming challenges.

Addressing emerging risks and uncertainties: Main policy considerations

Governments may need to act if regulatory uncertainties prevent the adoption of ICTs. This is especially the case if regulations designed for the pre-digital era inadvertently shield incumbents from new forms of competition. For example, removing regulatory barriers to entry into the mobile market would allow some vehicle manufacturers, whose fleets contain millions of connected devices, to become independent of mobile network operators. This would also strengthen competition.

Governments should support a culture of digital risk management (as promoted by the 2015 OECD Recommendation on *Digital Security Risk Management for Economic and Social Prosperity* [2015e]). Traditional security approaches might not fully protect assets in a digital environment, and are likely to stifle innovation. Frequent barriers to a culture of digital risk management, especially SMEs, include a lack of know-how, and a belief that digital security is a technical IT management issue rather than a business management issue. In response, some governments have promoted awareness raising, training and education for digital risk management. For example, under the French national digital security strategy, the French state secretariat in charge of Digital Technology, along with ministries and the National Cybersecurity Agency (ANSSI), will co-ordinate a cybersecurity awareness programme for professionals.

Barriers to Internet openness, legitimate or otherwise, can limit digitalisation. Frequently encountered barriers include technical conditions (such as Internet Protocol package filtering) and "data localisation" efforts (such as legal obligations to locate servers in local markets). The effects of barriers to Internet openness are particularly severe where data-driven services are weak due to poor ICT infrastructure. However, openness can present challenges, e.g. if it is exploited to conduct malicious activities. Accordingly, some barriers to Internet openness may have legal or security rationales.

Obstacles to the reuse, sharing and linkage of data can take many forms and should be examined. Technical obstacles can include constraints such as difficult machine readability of data across platforms. Legal barriers can also prevent data reuse and sharing. For example, the "data hostage clauses" found in many terms-of-service agreements can sometimes prevent customers from moving to other providers. Furthermore, non-discriminatory access to data, including through data commons, open data, and data portability, enables users to create value from data in ways that often could not be foreseen when the data were created.

Coherent data governance frameworks should be developed. Access to data should not necessarily be free or unregulated: a balance is needed between data openness (and the consequent social benefits of greater access and reuse of data), and the legitimate concerns of those whose privacy and IPRs may be negatively affected. This calls for a whole-of-government approach when applying and enforcing data governance.

Governments can promote the responsible use of personal data to prevent privacy violations. Governments could promote privacy-enhancing technologies and empower individuals through greater transparency of data processing, and greater data portability. Examples of such initiatives include midata in the United Kingdom and MesInfos in France. Governments may need to increase the effectiveness (i.e. resourcing and technical expertise) of privacy enforcement authorities.

Governments may need to assess market concentration and competition barriers using up-to-date definitions of the relevant markets and consideration of the potential consumer detriments of privacy violations. This may also require dialogue between regulatory authorities (particularly in the areas of competition, privacy and consumer protection).

Addressing emerging risks and uncertainties: Main policy considerations *(cont.)*

Further reflection is needed on the attribution of responsibility and liability for inappropriate data-driven decisions. Governments may have to assess whether existing regulations and legislation fully address the challenge of attributing responsibility and liability for damaging data-based decisions (as between decision makers and providers of data and data analytics). Multi-stakeholder dialogue at national and international level could help by exchanging best practices.

Careful examination is needed of the appropriateness of fully automated decision making, transparency requirements and required human intervention in areas where the potential harm of automated decisions could be significant. Transparency requirements may need to extend to the processes and algorithms underlying automated decisions. But such transparency requirements could come into tension with IPRs and the economic value of the processes and algorithms at the core of some businesses' operations. More studies are needed to determine how best to assess the appropriateness of algorithms without violating existing IPRs.

Bioproduction and the bioeconomy

Industrial biotechnology involves the production of goods from renewable biomass instead of finite fossil-based reserves. The biomass can be wood, food crops, non-food crops or even domestic waste. Expanding the bioeconomy is critical. Events in 2015 – such as COP21 and the Global Bioeconomy Summit – have propelled the bioeconomy concept to the forefront of politics. As Chapter 3 describes, an increasingly bio-based economy could help to bridge economic and environmental policy goals, and also help achieve such objectives as rural industrial development. At least 50 countries, including the G7 countries, have national bioeconomy strategies or related policies.

Much progress has occurred in the tools and achievements of industrial biotechnology. For example, several decades of research in biology have yielded synthetic biology and gene-editing technologies (Box 1.3). When allied to modern genomics – the information base of all modern life sciences – the tools are in place to begin a bio-based revolution in production. Bio-based batteries, artificial photosynthesis and micro-organisms that produce biofuels are just some of the recent advances. And in a breakthrough reported in early 2017, scientists have even succeeded in synthesising graphene from soy bean oil (discovered in 2002, graphene could have revolutionary implications in electronics and many other sectors, but until today has been hard to manufacture in significant amounts).

Notwithstanding the remarkable new biotechnologies, the largest medium-term environmental impacts of industrial biotechnology hinge on the development of advanced biorefineries (Kleinschmit et al., 2014). Essentially, a biorefinery transforms biomass into marketable products (food, animal feed, materials, chemicals) and energy (fuel, power, heat). Based on a recent OECD survey, Chapter 3 summarises international approaches to the development of advanced biorefineries.

Strategies to expand biorefining must address the sustainability of the biomass used. Governments can help to create sustainable supply chains for bio-based production. In particular, governments should urgently support efforts to develop comprehensive or standard definitions of sustainability (as regards feedstocks), tools for measuring sustainability, and international agreements on the indicators required to drive data collection and measurement (Bosch, van de Pol and Philp, 2015). Furthermore, environmental performance standards are needed for bio-based materials. Such standards are indispensable because most bio-based products are not currently cost-competitive with petrochemicals, and because sustainability criteria for bio-based products are often demanded by regulators.

Box 1.3. **What are these technologies?**

Genomics is a discipline that applies recombinant deoxyribonucleic acid (DNA), DNA sequencing methods and bioinformatics to sequence, assemble and analyse the function and structure of genomes. In many ways genomics is an information technology, although the code is not digital but genetic.

Green chemistry involves designing environmentally benign chemical processes, leading to the manufacture of chemicals with a lesser environmental footprint.

Metabolic engineering is the use of genetic engineering to modify the metabolism of an organism. It can involve the optimisation of existing biochemical pathways or the introduction of pathway components, most commonly in bacteria, yeast or plants, with the goal of high-yield production of specific molecules for medicine or biotechnology.

Synthetic biology aims to design and engineer biologically based parts, novel devices and systems as well as redesign existing natural biological systems.

Demonstrator biorefineries operate between pilot and commercial scales. Demonstrator biorefineries are critical for answering technical and economic questions about production before costly investments are made at full scale. But biorefineries and demonstrator facilities are high-risk investments, and the technologies are not proven. Financing through public-private partnerships is needed to de-risk private investments and demonstrate that governments are committed to long-term coherent policies on energy and industrial production.

Whereas initiatives for bio-based fuels have existed for some decades, little policy support has been given to producing bio-based chemicals. Bio-based production of chemicals could substantially reduce greenhouse gas (GHG) emissions (Weiss et al., 2012).

As Chapter 3 outlines, there are many areas where governments could support R&D and commercialisation in bioproduction and metabolic engineering (i.e. using genetic engineering to modify the metabolism of micro-organisms so that they make useful products). One example would be to support R&D on the convergence of industrial biotechnology with new environmentally benign chemical processes. Another is improving computation, data analytics and digital technologies for synthetic biology (which involves writing new genetic code) and metabolic engineering.

Many types of policy are needed to realise the potential of bio-based production, from public support for research, to development of sustainability measures for biomass, to product labelling schemes for consumers, to education and training initiatives for the workforce. The transition to an energy and materials production regime based on renewable resources will face technical and political obstacles and will take time. Earlier transitions, from wood to coal and then from coal to oil, were not complicated by the need to meet today's global challenges. But today's global challenges make the need for this new transition all the more urgent.

Bioproduction and industrial biotechnology: Main policy considerations

Governments could help to create sustainable supply chains for bio-based production. Monitoring and controlling the collection of crops and residues is a major task. There are currently no comprehensive or standard definitions of sustainability (as regards feedstocks), no ideal tools for measuring sustainability, and no international agreement on the indicators to derive the data from which to make measurements (Bosch, van de Pol and Philp, 2015). And at present there are no environmental performance standards for bio-based materials. Biomass disputes are already occurring and threaten to create international trade barriers. Global sustainable biomass governance is a patchwork of many voluntary standards and regulations. An international dispute settlement facility could help to resolve this issue.

Demonstrator biorefineries are critical for answering technical and economic questions about production before costly investments are made at full scale. Biorefineries and demonstrator facilities are high-risk investments, and the technologies are not yet proven. Financing through public-private partnerships is needed to help de-risk private investments.

A main challenge in bio-based production is its multidisciplinarity. Researchers will need to be able to work together across the disciplines of agriculture, biology, biochemistry, polymer chemistry, materials science, engineering, environmental impact assessment, economics and, indeed, public policy. Research and training subsidies will have to help create not only the technologies required, but also the technical specialists (Delebecque and Philp, 2015). There are some proven ways for governments to help tackle this challenge, such as by organising research degrees with a focus on business, not academic, outcomes.

Governments should focus on three objectives as regards regulations:

- Boost the use of instruments, in particular standards, so as to reduce barriers to trade in bio-based products.
- Address regulatory hurdles that hinder investments.
- Establish a level playing field for bio-based products relative to biofuels and bioenergy (Philp, 2015).

Better waste regulation could also boost the bioeconomy. For example, governments could ensure that waste regulations are less proscriptive and more flexible, enabling the use of agricultural and forestry residues and domestic waste in biorefineries.

Governments could lead in market-making through public procurement policies. Bio-based materials are not always amenable to public procurement as they sometimes form only part of a product (such as a bio-based screen on a mobile phone). Public purchasing of biofuels is much easier (e.g. for public vehicle fleets).

Tapping the potential of nanotechnology

In Chapter 4, Steffi Friedrichs examines nanotechnology and production. "Nano" is a prefix denoting one billionth of a given unit. For example, 1 nanometre (nm) is one billionth of 1 metre. The broadest definitions of nanotechnology include all phenomena and processes occurring at a length-scale of 1 nm to 100 nm (for comparison, a sheet of paper is about 100 000 nm thick). Interactions at this scale are fundamental to life and the material world. The nanoscale is the realm where individual atoms, which do not have material properties in their own right, bond with other atoms. This creates the smallest (nanoscale) functional units of materials, the properties, functionalities and processes of which are observed across the inorganic and biological worlds.

As Friedrichs explains, control of materials on the nanoscale is a general-purpose technology that has applications across production. Recent innovations include developments in such fields as quantum-effect computing (in the discipline of physics), invisible materials (in solid state chemistry), artificial tissue and biomimetic solar cells (in biology), and nanoscale devices used in medical diagnostics and therapeutics (enabled by nano-electro-mechanical systems created by engineers). Nanotechnology can help to replace energy-hungry production processes (such as the fabrication of solar cells in zone-melting processes) with low-cost processes (such as roll-to-roll printing of solar cells in ambient air). Nanotechnology makes flexible computer screens possible. And nanotechnology can underpin new advanced single-use products (such as lab-on-a-chip diagnostics).

Many large companies initially adopted nanotechnologies to enable process innovations, and to help reach environmental goals (e.g. by reducing the use of organic solvents by working with nanoparticles suspended in water). In addition, advanced nanomaterials are increasingly used in manufacturing processes for high-tech products (e.g. to polish electronic and optical components).

In the 1980s, science and technology foresight studies envisaged rapid advances from the initial discovery of material control on the nanometre scale, to the ultimate creation of any complex functional system from its smallest building blocks (Drexler 1986). These visions proved overly optimistic, underestimating the technical challenges involved. However, over the last ten years techniques for large-scale production of nanotechnology-based materials have improved significantly. In the short and medium term, nanotechnology will continue to improve existing products and production processes. Entirely new products and processes from nanotechnology-based innovations may arise in the long run. Chapter 4 describes policies needed to support the continuing advancement and use of nanotechnology.

Nanotechnology: Main policy considerations

Nanotechnology requires increased efforts in institutional and possibly international collaboration. The entirety of research and engineering tools required to set up an all-encompassing R&D infrastructure for nanotechnology might be prohibitively expensive. State-of-the-art equipment costs several million euros and often requires the construction of bespoke buildings. Moreover, some of the most powerful research instruments exist as prototypes only. It is therefore almost impossible to gather a comprehensive nanotechnology infrastructure within a single institute or even a single region. Consequently, nanotechnology requires inter-institutional and/or international collaboration to reach its full potential. Publicly funded R&D programmes should allow involvement of academia and industry from other countries. This would enable targeted collaborations between the most suitable partners. An example of such an approach is the Global Collaboration initiative under the European Union’s Horizon 2020 programme.

Support is needed for innovation and commercialisation in small companies. The relatively high cost of nanotechnology R&D hampers the involvement and success of small companies in nanotechnology innovation. Nanotechnology R&D is mainly conducted by larger companies. Large companies are better placed to assimilate nanotechnology due to their critical mass in R&D and production, their ability to acquire and operate expensive instrumentation, and their ability to access and use external knowledge. Policy makers could seek to improve SMEs’ access to equipment by: i) increasing the size of SME research grants; ii) subsidising/waiving service fees; or iii) providing SMEs with vouchers for equipment use.

Nanotechnology: Main policy considerations *(cont.)*

Interdisciplinarity must be supported and encouraged. Nanotechnology tends to thrive at the interface of traditional disciplines. This is where discipline-specific research and engineering infrastructures are available – favouring multidisciplinarity – and expert knowledge in traditional disciplines is pooled. Examples of such conducive environments include virtual networks, such as Germany has created to support biomedical nanotechnology, and research institutes such as the United Kingdom's Interdisciplinary Research Collaborations. As a general-purpose technology, nanotechnology has an impact on many industry sectors. Policy instruments may need to be designed in ways that facilitate multidisciplinary approaches.

Regulatory uncertainties regarding risk assessment and approval of nanotechnology-enabled products must be addressed in internationally collaborative approaches. Regulatory uncertainties regarding risk assessment and approval of nanotechnology-enabled products severely hamper the commercialisation of nano-technological innovation. This is because products awaiting market entry are sometimes shelved for years before a regulatory decision is made. In some cases, this has caused the closure of promising nanotechnology start-ups, while large companies have terminated R&D projects and innovative products. A 2016 OECD report investigated the treatment of some nanotechnology-enabled products in the waste stream, concluding that more needs to be done to safely integrate nanotechnology in its diverse uses (OECD, 2016b). Policies should support the development of transparent and timely guidelines for assessing the risk of nanotechnology-enabled products, while also striving for international harmonisation in guidelines and enforcement.

Policy should support novel business and innovation-funding models. Among other things, new models need to take account of the increasingly collaborative nature of R&D for complex inventions, and the advancing digitalisation of research and production processes. For example, policy makers need to find models under which pre-competitive data can be openly shared, without compromising the ability of universities to raise income.

3D printing, production and the environment

3D printing is expanding rapidly owing to falling printer and materials prices, the rising quality of printed objects, and innovation. The global 3D printing market is projected to grow at around 20% a year to 2020 (MarketsandMarkets, 2014). Recent innovations permit 3D printing with novel materials – such as glass and metals – as well as printing of multi-structure multi-material objects, such as batteries and drones. DNA printers and printing of body parts and organs from a person's own cells are under development. Research is advancing on 3D printing with programmable matter.[5] And hybrid 3D printers have been developed which combine additive manufacturing with computer-controlled machining and milling functions.

3D printing could augment productivity in a number of ways. For example, 3D printing of already-assembled mechanisms is possible, which could reduce the number of steps in some production processes. Design processes can be shortened, owing to rapid prototyping (Gibson, Rosen and Stucker, 2015). Objects can also be printed which are otherwise impossible to manufacture, such as metal components contained within other seamless metal components. Currently, most 3D printing is used to make prototypes, models and tools, with only 15% producing parts in sold goods (Beyer, 2014).

In manufacturing, machining is the main method used for prototyping and producing limited amounts of custom parts. 3D printing is already significantly altering the market for machined plastic and metal parts. For example, Boeing has replaced machining with 3D printing for over 20 000 units of 300 distinct parts (Davidson, 2012). However, machining is a small industrial niche, comprising no more than a few percent of the value of total manufacturing sales.

In Chapter 5, Jeremy Faludi, writing with Natasha Cline-Thomas and Shardul Agrawala, analyses the environmental impacts of 3D printing. As Chapter 5 explains, the expansion of 3D printing depends on the technology's near-future evolution in print time, cost, quality, size and choice of materials. The main factor driving or limiting expansion of 3D printing is the cost of switching from mass-manufacturing methods to 3D printing. Costs are expected to decline rapidly in coming years as production volumes grow (McKinsey Global Institute, 2013), although it is difficult to predict precisely how fast this technology will be deployed. Furthermore, the cost of switching is not the same across industries. 3D printing will rapidly penetrate high-cost, low-volume industries such as prototyping, automotive tooling, aerospace and some medical devices. But 3D printing will more slowly penetrate moderate-cost, moderate-volume industries.

The environmental effects of 3D printing on two important industrial technologies – machining and injection moulding – are particularly interesting to consider. These technologies represent two ends of a spectrum: single-unit prototyping and mass manufacturing. Even considering these restricted cases, the environmental impacts of 3D printing vary widely. Printer type, frequency of printer utilisation, part orientation, part geometry, energy use and the toxicity of printing materials all play a role. Some experimental systems already have far lower environmental impacts per part than injection moulding – perhaps 70% lower in some circumstances. Industry is not trending towards such systems, but policy could encourage socially desirable choices.

Two frequently claimed sustainability benefits of 3D printing – eliminating waste and transportation – fail to take into account the need for high purity materials that often cannot be recycled and the need for feedstock materials to be transported to the printing site. Many printing methods require such a high level of material purity that they discourage recycling.

Nevertheless, 3D printing can enable more sustainable material use because:

- It permits many materials to be shaped in ways previously possible only with plastics.
- It lowers barriers to switching between materials by reducing economies of scale in some processes.
- It can allow fewer chemical ingredients to yield more variation in material properties by varying printing processes.

3D printing of some parts can also lower environmental impacts because of how the parts are used, even if environmental impacts during their manufacture are high. This can happen in two ways: i) by reducing a product's weight or otherwise improving its energy efficiency (General Electric's lighter 3D printed jet engine parts improved fuel efficiency by 15% [Beyer, 2014]); and ii) by printing replacement parts for legacy products that would otherwise be discarded. For example, a washing machine no longer in production might be thrown away because a single part is broken. Having a digital file for the required part would help avoid such waste.

3D printing and sustainability: Main policy considerations

To support sustainability in 3D printing, policy should primarily encourage low-energy printing processes and low-impact materials with useful end-of-life characteristics. Printer design and operation can minimise energy use per printed part by: using chemical processes rather than melting material; using automatic switching to low-power states when idle; and maximising utilisation (sharing printers among users and, for some printer types, printing more parts simultaneously). Printers can also minimise material impacts by using compostable biomaterials. And printer design and operation can reduce waste by using less support material (printers often use support materials in addition to the modelling material). Policy mechanisms to achieve these priorities should include:

- Targeting financial grants or investments (either existing programmes or new funds) to commercialising research in these directions.
- Taking into account the interests of all stakeholders, examining how best to remove intellectual property (IP) barriers, so as to enable 3D printing of repair parts for legacy products that lack existing supply chains (such as the broken washing machine requiring a single part to be fixed, mentioned above). Theoretically, a consumer with a 3D printer could go to a computer, find the appropriate computer-aided design (CAD) file and print the new part. But most CADs are proprietary. One solution would be to incentivise rights for third parties to print replacement parts for products, with royalties paid to original product manufacturers as needed.
- Creation of a voluntary certification system to label 3D printers with different grades of sustainability across multiple characteristics. Such a voluntary certification system could be combined with preferential purchasing programmes by governments and other large institutions.

New materials and the next production revolution

In Chapter 6, David McDowell reviews recent developments in new materials and their many implications for product design and performance, as well as public policy. Advances in scientific instrumentation, such as atomic-force microscopes, have allowed scientists to study materials in more detail than ever before. Developments in computational simulation tools for materials have also been critical. Today, materials are emerging with entirely novel properties: solids with densities comparable to that of air; exotic alloys and super-strong lightweight composites; materials that remember their shape, repair themselves or assemble themselves into components; and materials that respond to light and sound, are all now realities (The Economist, 2015).

Progress in computation has allowed modelling and simulation of the structure and properties of materials to inform decisions on how the material might be used in products. Properties such as conductivity, corrosion resistance and elasticity can be intentionally built into new materials. This computation-assisted approach is leading to an increased pace of development of new and improved materials, more rapid insertion of known materials into new products, and the ability to make existing products and processes better (e.g. the possibility exists that silicon in integrated circuits could be replaced by materials with superior electrical properties). In the next production revolution, engineers will not just design products. They will also design the materials the products are made from (Teresko, 2008).

Among other things, the importance of new materials for manufacturing is reflected in the United States' Materials Genome Initiative (MGI). Introduced by President Obama in

June 2011, the MGI aims to halve the time, and lower the cost, to discover, develop, manufacture and deploy advanced materials.

The era of trial and error in materials development is coming to an end. A simulation-driven approach to materials development will reduce time and cost because, in searching for materials with the desired qualities, companies will be able to avoid the analysis of many candidate materials and simply design the desired qualities into materials from the start. Simulation will permit better products, such as stronger complex structures. Successful integration of materials modelling and data sciences into decision support for product development could also shorten the time between the discovery of materials and their commercial use. The Accelerated Insertion of Materials (AIM) programme, run by the United States' Defense Advanced Research Projects Agency (DARPA), has demonstrated such time savings. Large companies, too, will increasingly compete in terms of materials development. This is because the combination of a proprietary manufacturing process applied to proprietary materials creates long-term competitive differentiation (The Economist, 2015).

New materials and the next production revolution: Main policy considerations

Policy making at national and international levels can strongly influence the development of the materials innovation ecosystem, broaden the potential pool of collaborators, and promote adoption of more efficient investment strategies. No single company or organisation will be able to own the entire array of technologies associated with an e-collaborative materials innovation ecosystem. Accordingly, a public-private investment model is warranted, particularly with regard to building cyber-physical infrastructure and developing the future workforce.

New materials will raise new policy issues and give new emphases to longstanding policy concerns. For example, new cybersecurity risks could arise because, in a medium-term future, a computationally assisted materials "pipeline" based on computer simulations could be hackable. Progress in new materials also requires effective policy in areas important for pre-existing reasons, often relating to the functioning of the science-industry interface. For example, well-designed policies are needed for open data and open science (e.g. for sharing simulations of materials structures or for sharing experimental data in return for access to modelling tools [Nature, 2013]). Advances in new materials also require close collaboration between industry, universities, research funding agencies and government laboratories.

Interdisciplinary research and education are needed. Materials research is inherently interdisciplinary. Beyond traditional materials science and engineering, contributions come from physics, chemistry, chemical engineering, bio-engineering, applied mathematics, computer science, and mechanical engineering, among other fields. In education, students who will become experts in materials synthesis, processing or manufacturing must understand materials modelling and theory, while modellers and theorists must understand the challenges faced in industry.

Policy co-ordination is needed across the materials innovation infrastructure at national and international levels. Major efforts are under way to develop the early materials information infrastructure and associated data standards in professional societies (Robinson and McMahon, 2016). A need for international policy co-ordination arises from the necessity of federating elements of the cyber-physical infrastructure across a range of European, North American and Asian investments and capabilities, as it is too costly (and

New materials and the next production revolution: Main policy considerations *(cont.)*

unnecessary) to replicate resources that can be accessed via web services with user support. Ultimately, good policies are required because of the need to change the culture of sharing data and, in particular, to facilitate a pre-competitive culture of e-collaboration.

Deliberation between research bodies, firms, government research laboratories, standards organisations and professional societies working to develop new and improved materials have predominantly addressed the compatibility of data formats. But deliberation needs to evolve towards a focus on how to use these data to support decisions in materials discovery and development, along with tackling many of the foregoing policy issues. Access to high-performance computing and cloud storage is important, to which pre-competitive public-private consortia and government policy can contribute. Initiatives such as the Integrated Computational Materials Engineering expert group (ICMEg) in Europe are wrestling with these issues.

The diffusion of new production technologies: What can governments do?

While great wealth can come from creating technology, most companies and most countries – especially developing countries – will mainly be technology users. For them, fostering technology diffusion should be a primary goal. Even in the most advanced economies, diffusion can be slow or partial. For example, a 2015 survey of 4 500 German businesses found that just 18% were familiar with the term "Industry 4.0" and only 4% had implemented digitalised and networked production processes or had plans to do so (ZEW-IKT, 2015).

The diffusion issue is twofold. First, it is about increasing new-firm entry and the growth of firms which become carriers of new technology. OECD research over recent years has highlighted the role of new and young firms in net job creation and radical innovation. But Criscuolo, Gal and Menon (2014) find declining start-up rates across a range of countries since the early 2000s. Governments must attend to a number of conditions which affect this dynamism, such as timely bankruptcy procedures and strong contract enforcement (Calvino, Criscuolo and Menon, 2016).

Second, diffusion is about established firms implementing productivity-raising technologies. In this second case, an important issue is that small firms tend to use key technologies less frequently than larger firms. In Europe, for example, 36% of surveyed companies with 50 to 249 employees use industrial robots, compared to 74% of companies with 1 000 or more employees (Fraunhofer, 2015). As Chapter 2 shows, even though cloud computing has increased the availability and affordability of computing resources, small firms in almost all countries use this technology less than large firms.

Diffusion is affected by national and international conditions

Several factors, operating at national and international levels, shape the diffusion process. These include: i) global connections via trade – which is a vehicle for technology diffusion and an incentive for technology adoption – and foreign direct investment (FDI); ii) the international mobility of skilled labour; iii) connections and knowledge exchange within national economies, such as the interaction between scientific institutions and businesses; iv) the existence and development of standards (the semiconductor industry, for example, uses over 1 000 standards [Tassey, 2014]); vi) the extent of businesses' complementary intangible investments in R&D, skills, managerial capabilities and other forms of knowledge-based capital (OECD, 2015c); and vii) the efficiency of the processes by which firms can attract the resources they need to grow. If firms which could lead the next production revolution are unable to attract the human and financial resources to grow, the future development and diffusion of technology will be stunted.

As examined in a number of recent OECD reports, the causes of inefficient resource allocation can include a lack of product competition, rigid labour markets, disincentives for firm exit, and barriers to growth for successful firms, as well as policy conditions. Policies matter greatly. For example, the sensitivity of firms' investment in fixed capital to changes in their patent stock is more than tripled where employment protection legislation is relatively lax (such as in the United States), compared with countries where it is stringent (such as Portugal). And the sensitivity of capital investment to changes in the patent stock is almost double in countries where contract enforcement is less costly (such as Norway), relative to countries where it is more costly (such as Italy) (Andrews, Criscuolo and Menon, 2014).

Beyond framework conditions, institutions for technology diffusion can be effective

In Chapter 7, Philip Shapira and Jan Youtie assess the functions and impacts of institutions for technology diffusion. As the authors explain, institutions for technology diffusion are intermediaries with structures and routines that facilitate the adoption and use of knowledge, methods and technical means. Innovation systems contain multiple sources of technology diffusion, such as universities and professional societies. But some of the institutions involved, such as technical extension services, tend to receive low priority in innovation policy overall. However, such institutions can be effective, if properly designed, incentivised and resourced.

The classic rationale for supporting institutions and mechanisms for technology diffusion builds on information deficiency and asymmetry and other market failures. Enterprises (especially SMEs) frequently lack information, expertise and skills, training, resources, strategy and confidence to adopt new technologies. Suppliers and private consultants can face high transaction costs in trying to diffuse technologies. And finance for scale-up and implementation is not always forthcoming. Technology diffusion institutions seek to guide and support enterprise adoption capabilities and investment choices in new technology. In the fast-moving environment of next-generation production technologies, the conventional market failure rationales for institutional intervention are likely to grow in importance. Potential users will need support to sift through burgeoning amounts of information and make decisions in a context of rapidly changing technologies and expertise requirements.

New diffusion initiatives are emerging, some of which are still experimental

The need for new strategies to promote institutional change, knowledge exchange, capacity development, and demand-led initiatives for technology diffusion has given rise to new initiatives, some of which are experimental. New production technologies have stimulated partnerships that cross sectoral boundaries and address problems of scaling up from research to production. Alongside established applied technology centres, such as the Fraunhofer institutes in Germany, there is an increase in partnership-based approaches (see also Chapter 10). Manufacturing USA, for example, uses private non-profit organisations as the hub of a network of company and university organisations to develop standards and prototypes in many areas, such as 3D printing and digital manufacturing and design (see also Chapter 11 for a comprehensive examination of Manufacturing USA).

Analogous to the rise of open sharing of research articles and data is the emergence of libraries promoting sharing of technological building blocks. For example, BioBricks is an open-source standard developed at Massachusetts Institute of Technology (MIT) to enable shared use of synthetic biology parts through the Registry of Standard Biological Parts. Such open-source mechanisms in biotechnology exist against a backdrop of traditional proprietary biotechnology approaches.

Policies to promote diffusion address funding for activities between research and commercialisation, and gaps in research commercialisation. For example, the Innovation Corps (I-Corps) programme was established by the US National Science Foundation (NSF) in 2011 to accelerate commercialisation of science-intensive research. Teams of researchers and budding entrepreneurs receive grants to attend training, which encourages ongoing interaction with customers and partners. The programme enhances the knowledge of participants and their capacity to start companies around NSF-funded research (Weilerstein, 2014).

Attention to the procurement of innovation by government agencies has also grown across many countries, often targeted at SMEs. Incentives such as R&D tax credits, regulations and standards are being used to encourage pre-commercial R&D activities, such as feasibility studies and prototyping. The effectiveness of technology diffusion institutions depends in part on firms' absorptive capabilities. This suggests the importance of efforts to foster demand through such mechanisms as innovation vouchers, which encourage users to engage with knowledge or technology suppliers. Several countries (including the United Kingdom, Ireland and the Netherlands) have promoted innovation vouchers.

The diffusion of new production technologies: Main policy considerations

Policy needs to ensure the integration of technology diffusion and its institutions into efforts to implement the next production revolution. Policy makers tend to acknowledge the critical importance of technology diffusion at a high level, but to overlook technology diffusion in the subsequent allocation of attention and resources.

Technology diffusion institutions need realistic goals and time horizons. Introducing new ways to integrate and diffuse technology takes time, patience and experimentation. Yet many governments want quick riskless results. Evaluation metrics should emphasise longer-run capability development, rather than short-term incremental outcomes.

Misalignment can exist between the aims of technology diffusion institutions and their operational realities. While some production technologies are promoted for their ability to address societal challenges, funding and evaluation models in many public technology diffusion institutions prioritise revenue generation. Furthermore, there is often a focus on disseminating the latest advanced technology, when many enterprises and users do not use even current technologies to their fullest extent and lack absorptive capabilities for sophisticated technologies.

Policy making needs better evidence and a readiness to experiment. A better understanding of effective organisational designs and practices is vital. Concerns over governmental accountability combined with ongoing public austerity in many economies could mean that current institutions will be reluctant to risk change, slowing the emergence of next-generation institutions for technology diffusion.

The diffusion of new production technologies: Main policy considerations *(cont.)*

There are also practices that policy makers should avoid. Efforts to diffuse new technologies often target predictable early adopters. These tend to be multinationals, high-technology start-ups, and the small number of companies involved in technology development. Policy should not just target these likely early adopters, but should also focus on the much larger number of existing SMEs. And policies to support institutions for technology diffusion should not be presented as programmes to restore lost manufacturing jobs. Upgrading the ability of manufacturing communities to absorb new production technologies will take time (five to ten years or more). Accordingly, technology diffusion institutions need to be empowered and resourced to take longer-term perspectives.

Public acceptance and new technologies

In Chapter 8 David Winickoff addresses the issue of public acceptance of new technologies and how policy can affect public attitudes. In the past, public concerns have blocked the development and implementation of some new technologies. This has happened even when a technology's technical and economic feasibility has been demonstrated, where there has been a rationale for adoption, and where large investments have been made. For example, many countries invested in the construction of nuclear reactors in the 1960s and 1970s. Even in the face of expert opinion avowing safety, public protests often halted their use (Winner, 1986).

Public pressure can shape regulations that condition the adoption of technology. For example, in biotechnology, public controversies over genetically modified organisms (GMOs) have had a major impact on regulation and approval of new crops in Europe (Watson and Preedy, 2016). But public concerns can also result in increased safety and acceptability. For example, scientific studies and environmental protest in the 1960s and 1970s led to stricter regulation of pesticides and other chemicals (Davis, 2014). Similarly, regulation can facilitate technology adoption by stipulating the terms of acceptable use: activism in the 1960s over vehicle safety led to stricter safety requirements and shaped the development of the automobile industry (Packer, 2008).

Biotechnology has been the subject of persistent public conflicts over societal risks. In both developed and developing countries, genetically modified (GM) crops have raised concerns around health and safety risks, the capacity to contain and reverse their release, and the effects of IP on concentration in the structure of the agro-food industry (Jasanoff, 2005). Such concerns have been resolved differently in different countries. Starkly contrasting regulatory approaches growing out of distinct public attitudes to biotechnology have resulted in disruptions to international trade and have even led to dispute settlement at the World Trade Organization (WTO) (Pollack and Shaffer, 2009). Governments will have to anticipate public concerns around the most recent biotechnological advances, especially gene editing.

Other technologies addressed in this report have raised public concerns of different kinds. Some considerations have to do with risk, such as how nanotechnologies might affect human health (see Chapter 4). Government programmes to collect and use big data have also raised public concerns. For example, in the United Kingdom, failure to address privacy and access questions triggered a major public controversy among clinical physicians, disease advocacy groups and the larger public, undermining trust in central health authorities. The next production revolution could raise societal issues not seen before. For example, as machine autonomy develops, who will be responsible for the outcomes that machines give rise to, and how will control be exercised?

Public acceptance and new technologies: Main policy considerations

Having realistic expectations about technologies can help maintain trust. In areas of emerging technology, "hype" must be avoided. For example, stem cell research has involved a pattern of inflated predictions by scientific communities, funding agencies and the media (Kamenova and Caulfield, 2015).

Science advice must be trustworthy. There is a close connection between public resistance to novel technologies and the disruption of trust in public scientific and regulatory authorities. In the late 1990s in the United Kingdom a public controversy arose about how government regulators failed to address uncertainties in their risk assessment and management strategies around bovine spongiform encephalopathy (BSE), or "mad cow disease". This episode undermined the trust afforded to regulators on the risks of GMOs soon after (Pidgeon, Kasperson and Slovic, 2003). Countries must make systems of expertise more robust by encouraging exchanges with the public, communicating clearly about sources of uncertainty, and in key institutions making processes of appointment and operation more accountable (Jasanoff, 2003).

Societal assessment of technology can inform science and technology policy. Innovation policy in many OECD countries is now guided by forms of societal technology assessment carried out by a mix of actors, including national ethics committees and other government bodies tasked with taking a broad view of social, health and safety risks. These assessments involve formal risk analysis but can also consider longer-term social implications of technologies not easily reduced to immediate health and safety risks.

Ethical and social issues should be included in major research endeavours. Since the Human Genome Project (HGP), science funders in many countries have sought to integrate attention to ethical, legal and social issues. The planners of the HGP recognised that mapping and sequencing the human genome would have profound implications for individuals, families and society, and so they allocated over 3% of their budget to the ethical, legal and social implications of that research. Since then, efforts have been made in many countries to mainstream social science and humanities work into funding streams. The next generation of these approaches integrates social considerations not at the end of technology pipelines, but in the course of their development. This includes the European Union's Horizon 2020 programme and the US National Nanotechnology Initiative (NNI).

Public deliberation is important for mutual understanding between scientific communities and the public, and should inform innovation policy. Deliberation can take various forms. Citizen panels and town hall meetings have been pioneered in Denmark and elsewhere. Deliberation can also take place in the context of national advisory processes and public inquiries, which should include dedicated processes for public engagement and the reception and processing of public concerns.

The role of foresight in shaping the next production revolution

As Attila Havas and Matthias Weber describe in Chapter 9, greater foresight in science and technology is sought by most governments. A goal of the America Competes Act, for example, is the identification of emerging and innovative fields. Better anticipation of trends could clearly assist policy development and the allocation of research funds and other resources.

Foresight is a specific type of prospective analysis aimed at thinking about and shaping the future. Foresight processes aim to systematically and transparently identify and assess social, technological, economic, environmental and policy conditions that affect aspects of the future. Foresight processes are action-oriented, participatory (often involving researchers, business people, policy makers and citizen groups), and consider multiple futures. Prediction is not the primary goal. In developing roadmaps and examining projections, foresight assists preparation for many possible futures. In addition, as Chapter 9 describes, the process of foresight can itself bring important benefits for institutions and policy making.

Foresight can – and should – take many forms, varying in thematic coverage, methods and time horizons. Several important recent foresight exercises have focused on manufacturing and production, such as NAE (2015) and Foresight (2013).

Governments can easily be trapped by the need to deal with the short term. Foresight provides space for longer-term thinking and for examining different possible futures. In uncertain times, thinking in terms of multiple future states is a precondition for devising policies to cope with unexpected developments. Furthermore, in a complex world, many phenomena cannot be understood in isolation. They must be seen from a number of viewpoints. The history of technological prognoses is littered with opinions which were enormously off-target, even among practitioners intimate with the technologies involved.[6] Such errors underscore the importance of drawing on multiple perspectives. Foresight involving participatory methods can incorporate the needed diversity.

Foresight processes can also help to mobilise and align stakeholders. Most foresight activities not only explore possible futures, they also seek a common understanding of what a desirable future might be. Such visions and – associated to them – operational roadmaps, can be instruments for assembling key players around a shared agenda. By involving participants from different policy domains, policy co-ordination can also be fostered horizontally (across policy domains, or between parliament and government) and vertically (between ministries and executive agencies).

Foresight processes: Main policy considerations

Governments can create conditions which aid effective foresight. Foresight must be appropriately embedded in decision-making processes. Foresight processes should operate close enough to decision making to have influence, but distant enough for intellectual autonomy. Foresight should be orchestrated with policy cycles to ensure that futures intelligence is available at the right time. And some form of institutionalisation – through regular programmes and/or the establishment of dedicated organisations – is needed to create a foresight culture. One-off exercises are unlikely to yield the greatest impacts on policy making. A sustained effort is also required to create the competences for conducting foresight.

Foresight processes have the potential to enlarge and renew the framing of policy issues. In a connected way, foresight can help to induce organisational innovations. Government bodies tend to be organised by rigidly demarcated policy domains. Organisational structures can lag behind fast-changing scientific and technological fields. In such cases, it can be difficult to find a proper place for cross-cutting research or for new ways of directing research (e.g. in shifting from science and technology-led research to societal challenge-driven research). Government bodies can also be insular, with the same participants sometimes repeatedly involved in decision making. Foresight processes can help to offset the effects of such conditions.

Sound science and R&D policies are important

The technologies examined in this report result from science. Microelectronics, synthetic biology, new materials and nanotechnology, among many others, have arisen because of advances in scientific knowledge and instrumentation. Publicly financed basic research has often been critical. For decades, for example, public funding supported progress in AI, including during unproductive periods of research, to the point where AI today attracts huge private investment and has critical uses in production.

Many important research breakthroughs have come from basic science, with applications that were not initially foreseen. For example, Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR-Cas9), was nominated by *Science* as the "Breakthrough of 2015". This technology can be traced to an accidental discovery during research on the *Escherichia coli* (*E.coli*) gene in the late 1980s. CRISPR-Cas9 permits changes in a DNA sequence at precise locations on a chromosome. This makes the design and construction of organisms with desired traits easier and cheaper. The use of CRISPR-Cas9 has spread quickly across industries and fields. In a similarly fortuitous way, greater understanding of the principles of biological self-construction is finding unexpected application in bottom-up intelligent self-assembly of devices (indeed, systems and materials for micro-scale self-assembly of devices have been developed using manmade viruses to guide the process[7]).

Not all countries or companies can be major technology producers. But countries with greater research capabilities in such fields as computing, biology, physics and chemistry could enjoy first-mover advantages in a number of industries. Chapter 2 shows that invention of technologies related to data-driven innovation is concentrated in only a few countries, a pattern seen in most fields in this report.

The complexity of many emerging production technologies exceeds the research capacities of even the largest individual firms (Chapters 4 and 5 give examples in nanotechnology and new materials respectively). Tassey (2014) makes the same point with respect to nanoelectronics and other emerging production technologies. The complexity of many of the research challenges is reflected in a spectrum of public-private research partnerships discussed, in particular, in Chapters 10 and 11.

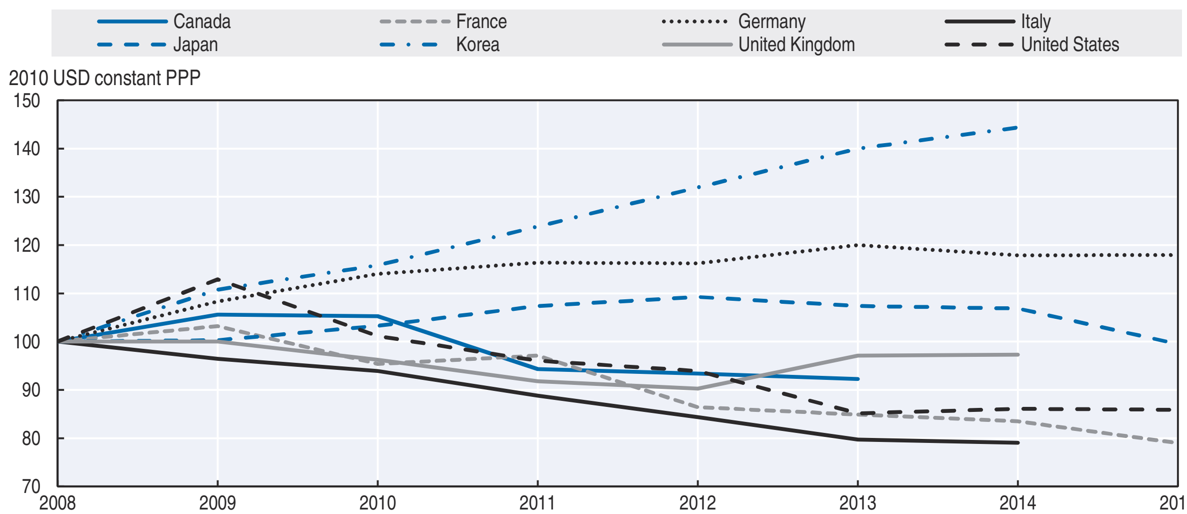
In examining new production technologies, this report has identified many possible targets for government supported R&D and commercialisation. These range from quantum computing (Chapter 2), to advancing the use of data analytics and digital technologies in metabolic engineering (Chapter 3), to the development of bio-friendly feedstock for 3D printers (Chapter 5). Across fields of science and technology, hundreds more themes could be raised.[8]

Many policies determine the strength of science and research systems and their impacts on production

Many policy choices determine the strength of science and research systems and their impacts on production. One issue is the scale of public support for research, which has fallen in recent years in some countries (Figure 1.1).

Figure 1.1. **Government budget appropriations or outlays for R&D (selected countries)**

Index: 2008 = 100



Source: Calculations based on the OECD Research and Development Statistics – "Government Budget Appropriations or Outlays for Research and Development" (GBAORD) dataset. Data extracted from *IPP. Stat* on 14 March 2017.

StatLink http://dx.doi.org/10.1787/888933473726

Besides the scale of public support for basic and applied research, policy makers need to be attentive to such matters as: the procedures for allocating funds for public research; a variety of institutional features and incentives which facilitate open science; the frameworks that provide incentives for firms, public researchers and public research institutes to commercialise research, while protecting the public interest; the development of well-designed public-private partnerships; the implementation of efficient, transparent and simple migration regimes for the highly skilled; the facilitation of linkages and networks among researchers across countries; and the creation of a judicious evidenced-based mix of support using both supply- and demand-side instruments.

Many of the critical research challenges are multidisciplinary and systemic

In Chapter 10, Eoin O'Sullivan and Carlos López-Gómez review emerging manufacturing R&D priorities and policies across countries. The chapter highlights that in supporting manufacturing R&D, policy makers are not only prioritising particular technology research domains, they are also designing institutions, programmes and initiatives to ensure that research results are developed, demonstrated and deployed in industrial systems. The chapter shows that there is growing attention to the themes of convergence (of research disciplines, technologies and systems), scale-up (of emerging technologies), and national economic value capture (from manufacturing innovation). These policy themes have in turn resulted in manufacturing research programmes and institutions adopting a broader range of research and innovation functions, beyond basic research, creating closer linkages between key innovation system actors, including more explicit requirements for interdisciplinary and inter-institutional collaborations, and providing new types of innovation infrastructure (tools, enabling technologies and facilities) to support convergence and scale-up.

O'Sullivan and López-Gómez show that government manufacturing research priorities and the approaches to institutional design reflect national differences in industrial and research strengths. In Germany, for example, emphasis has been placed on the integration of digital technologies into industrial production machinery and "smart factories", with particular attention to embedded systems, cyber-physical systems and the IoT. In Japan, the central government has recently emphasised the integration of advanced robotics and AI, and the integration of capabilities across specialist supply chains.

Common emerging features in new government-funded manufacturing R&D institutions, programmes and initiatives highlighted in Chapter 10 include the adoption of innovation support functions beyond basic R&D (e.g. prototype demonstration, training and supply chain development) and an increased focus on "grand challenges" (related to issues such as sustainable manufacturing, nanomanufacturing and energy storage).

O'Sullivan and López-Gómez observe that identifying priorities for government-funded manufacturing research programmes and initiatives is increasingly challenging. This is due to convergence among technologies and the growing complexity of modern manufacturing. To assess the impact of R&D investments – and decide where policy efforts should focus – policy makers need to take account of the increasingly blurred boundaries among manufacturing research domains. Technology R&D programmes can be too "siloed" if mechanisms are not put in place to support multidisciplinary and challenge-led endeavours. Many research challenges will need to draw on traditionally separate manufacturing-related research fields (such as advanced materials, production tools, ICT, and operations management). And many government-funded research institutions and programmes have been limited to carrying out research, without the freedom to adopt complementary innovation activities or connect to other innovation actors. As a result, government-funded research institutions and programmes are sometimes unable to bring together the right combination of capabilities, partners and facilities to address challenges of scale-up and convergence.

The authors of Chapter 10 point out that traditional performance indicators may not adequately incentivise efforts to enhance institutional linkages, strengthen interdisciplinarity and encourage research translation and scale-up. Better evaluation of institutions and programmes may need new indicators, beyond traditional metrics (such as numbers of publications and patents), including in areas such as: successful pilot line and test-bed demonstration, development of skilled technicians and engineers, repeat consortia membership, SME participation in new supply chains, and contribution to the attraction of FDI. Policy makers should assess whether performance indicators properly account for the systemic nature of the next production revolution.

Investments are often essential in applied research centres and pilot production facilities to take innovations from the laboratory into production. Developing linkages and partnerships between manufacturing R&D stakeholders is also critical. This, as noted earlier, reflects the scale and complexity of innovation challenges in advanced production. Meeting these challenges requires diverse capabilities and infrastructure which may be distributed across many innovation actors. For example, some manufacturing R&D challenges may need expertise and insight not only from manufacturing engineers and industrial researchers, but also designers, suppliers, equipment suppliers, shop floor technicians, and users.

Manufacturing R&D infrastructure also requires the right combinations of tools and facilities to address the challenges and opportunities of convergence and scale-up. Advanced metrology, real-time monitoring technologies, characterisation, analysis and testing technologies, shared databases, and modelling and simulation tools are just some of the tools and facilities concerned. Also needed are demonstration facilities such as test beds, pilot lines and factory demonstrators that provide dedicated research environments with the right mix of tools and enabling technologies, and the technicians to operate them.

The rise of advanced manufacturing institutes in the United States

In the decade of the 2000s, US manufacturing employment fell by one-third, 64 000 factories closed, manufacturing capital investment and output suffered, and productivity growth declined. Studies suggested that the decline in production capability was affecting the United States' innovation capacity, long viewed as the country's principal economic strength. In Chapter 11, William Bonvillian examines the origins, development of, and prospects for what was the main policy response to these circumstances, the National Network of Manufacturing Institutes (renamed Manufacturing USA in 2016).

The goals of the manufacturing innovation institutes which make up Manufacturing USA are to foster advanced manufacturing through collaboration between industry (both small and large firms), universities and government, to develop new production technologies and processes, and to provide workforce education. The range of technologies addressed is considerably broader than in many other national initiatives for advanced manufacturing (Box 1.4). The federal award to each new institute over a five-year period ranged from USD 70 million to USD 120 million. The consortium of firms, universities and state governments backing each new institute was required to at least match the federal government's investment.

Box 1.4. **The technological breadth of Manufacturing USA**

At the beginning of 2017 there were a total of 14 institutes, eight sponsored by the US Department of Defense (US DoD), five by the US Department of Energy (US DoE) and one by the National Institute for Standards and Technology (NIST). While Germany's Industry 4.0 (Plattform Industrie 4.0) initiative emphasises the IoT, the areas addressed by the US institutes are much wider and suggest how far-reaching a revolution in manufacturing could be. The current institutes are: the National Additive Manufacturing Innovation Institute (NAMII); the Institute for Advanced Composites Manufacturing Innovation (IACMI); the Digital Manufacturing and Design Innovation Institute (DMDII); the Lightweight Innovations for Tomorrow (LIFT) Institute, which addresses lightweight and modern metals; Power America, for next-generation power electronics; the American Institute for Manufacturing (AIM) Photonics; NextFlex, for flexible hybrid electronics; Advanced Functional Fabrics of America (AFFOA); the Smart Manufacturing Innovation Institute; the Rapid Advancement in Process Intensification Deployment (RAPID) Institute; the Advanced Regenerative Manufacturing Institute (ARMI); the Institute for Reducing Embodied Energy And Decreasing Emissions (REMADE) in Materials Manufacturing; and the Advanced Robotics Manufacturing (ARM) Institute.

Only a few of the new institutes have been operating long enough to have their progress evaluated against their mission statements. But lessons and challenges are already evident. A number of these lessons are US-centric, having to do for instance with the balance between federal and state responsibilities. But other lessons reiterate findings raised elsewhere in this report, including: a possibly problematic assumption that the institutes can become financially independent in five years (see also Chapter 7 on the danger of short-termism in policies to reinvigorate manufacturing innovation); ensuring governance models suited to the task of building lasting collaborations across a wide range of firms and researchers, not only for research but also for testing, technology demonstration and feedback, and product development; building an overarching support network to ensure that common problems are studied and shared by the institutes (many lessons have been learned about how to constitute governing boards and legal structures, how to manage IP, how to set up tiers of participants, how to organise regional outreach and education efforts, and so forth); ensuring that, while technology development is central, the institutes build in the additional tasks required for technology readiness levels (TRL) 5-7, further down the innovation pipeline, so that the evolving technologies can be implemented, especially by small and medium-sized firms; and building capacities in workforce training and engineering education, especially because agency contract and programme officers at the institutes tend to be technologists, not education experts.

Technological change also raises challenges for the IP system

The future of emerging production technologies could be affected by how IP and patent systems adapt. One among a number of challenges to the IP system comes from the ability to digitalise physical objects. Governments need to ensure the suitability of IP rules in the context of rapid technological change (Box 1.5).

Box 1.5. **Technological change and the near future of IP**

AI is far from being able to invent as humans do. However, certain software can already, or will soon be able to, produce patentable inventions. This is notably the case in chemistry, pharmaceuticals and biotechnology. In these fields many inventions consist in creating original combinations of existing molecules to form new compounds, or in identifying new properties of existing molecules. For example, KnIT, a machine-learning tool developed by IBM, was successfully run to identify kinases with specific properties among a set of known kinases. Those properties were then tested experimentally. Hence the specific properties of those molecules were discovered by software, and patents were filed for the inventions.

At some point, machines will assume a more prominent role than humans, and the question might arise as to whether a person with ordinary skills in the art but equipped with the right software might have produced the same invention without creativity. In such a case, the inventions would not be considered patentable, as they would not embody an “inventive step” (the minimal threshold of non-obviousness required for a patent to be granted).

3D printing will enhance the trend towards digitisation of physical objects. Digitisation of music, images and text from the mid-1990s on has transformed the industries concerned, with a pivotal role played by copyright. Digitisation has drastically reduced the cost of copying, creating, accessing and diffusing music. As the Internet became the major marketplace for music in the 2000s, and as few legal places to trade music existed, the lower cost of copying weakened copyright protection (despite measures to stop alleged piracy).

Box 1.5. **Technological change and the near future of IP** *(cont.)*

As a result, more music was bought online. Recording companies and other intermediaries saw their incomes fall and artists sought complementary income sources (such as ticket sales from live concerts and sales of T-shirts). At the same time the number of records issued increased and new creations and creators flourished. Might the same happen to digitised physical objects?

Scanners are available which allow many objects to be digitised. Being able to digitise physical things makes their distribution on the Internet possible, along with modification of the source code (when this is open). Digitisation allows households to manufacture goods which are not mass produced, most often based on designs downloaded from the Internet. Creators might post their creations on the Internet, for sharing or for sale to customers. In some industries, 3D printing might have a similar impact to that which the Internet had on the music industry, making innovation easier for all. Some Internet sites already offer digital objects, and they are often open source (so the objects can be printed and also modified). The possibility of copying and modifying objects which are wholly or in part (via some of their components) IP protected might raise new challenges.

3D printing might also create complications in connection with patent eligibility. For example, if 3D printed human tissue improves upon natural human tissue, it may be eligible for patenting, even though naturally occurring human tissue is not.[1] 3D printing might also challenge trademarks and copyright (for three-dimensional items like jewellery and sculptures). Infringement could be difficult to detect as it would often take place at home. A policy challenge will be how to preserve IP, which is necessary for incentivising certain types of innovation, while not hampering the diffusion of 3D printing and the flourishing of types of innovation which could accompany 3D printing.

Development of the IoT is also likely to force a common understanding of ownership rights regarding the data created by connected devices. A sensor might be manufactured by one company, operate in a system developed by another, and be deployed in an environment (such as a person's body) owned by a third. Agreement will be needed on who has which rights to the resulting data.

1. These examples are from Nemec and Voorhees (2014).

Education and skills systems need constant attention

Rapid technological change challenges the adequacy of skills and training systems. While this report does not contain a chapter on skills, various chapters document that for some production technologies current skills supply is insufficient. Indeed, the topic of skills is rarely absent from current discussions of production in any OECD country.

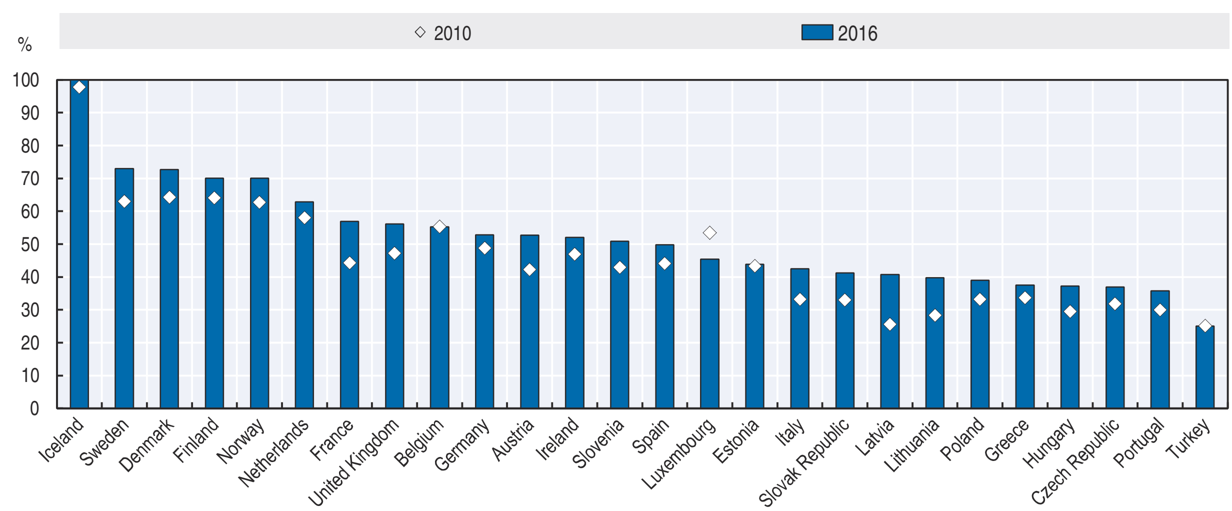
Policies that improve the efficiency of skills matching in labour markets are essential and support productivity (OECD, 2015c). How new production technologies relate to the process of skills matching may primarily concern a possible increase in the magnitude or speed of change. As previously noted, the pace and scope of technology-driven labour market changes is uncertain. But many types of work are predicted to decline or disappear. For example, sensor-based predictive maintenance, self-organising production and 3D printing of complex objects could eliminate jobs, respectively, for traditional service technicians, production planners, and workers in assembly and inventory management. But those same technology uses could also give rise to new occupations. For example, predictive maintenance will bring novel work in system design and data science. Self-organising production will require specialised data modellers. And 3D printing will create jobs for computer-aided designers. As robots are deployed more widely, demand will rise for robot co-ordinators to oversee robots and respond to malfunctions. A particularly highly demanded new job could be that of industrial data scientist (Lorentz et al., 2015).

In more general terms, new jobs are likely to be increasingly skilled (tasks performed within occupations have become more complex since the 1980s and the complexity increased most quickly in occupations undergoing significant computerisation [Spitz-Oener, 2006]). Demand for skills that compete with machines is also likely to fall, while demand for skills that complement machines is likely to rise. The (current) technical limits on automation also suggest other skills which might predominate in future production jobs, such as adaptability, problem solving and common sense (Davis and Marcus, 2015).

Digital skills could become increasingly important for most workers. Many firms consider a lack of digital skills to be a constraint (Capgemini, 2013). In 2013, more than 60% of European workers stated that their digital skills were inadequate to apply for a new job (OECD, 2014) (Figure 1.2).

Figure 1.2. **Computing is becoming a more common part of the work environment**

Share of employed people using an Internet-connected computer at work



Source: OECD (2017), *ICT Access and Use by Businesses database, http://stats.oecd.org/index.aspx?DatasetCode=ICT_BUS* (accessed in March 2017).

StatLink http://dx.doi.org/10.1787/888933473731

Tackling an uneven distribution of skills is also a key to lowering wage inequality. Among other reasons, this is because work requiring lower educational attainment is more susceptible to automation (Frey and Osborne, 2013). Recent evidence lends support to this prediction: Graetz and Michaels (2015) find that industrial robots have reduced hours worked primarily for low-skilled workers, with less pronounced declines for workers with mid-level skills.

Some new production technologies raise the importance of interdisciplinary education and research. For example, progress in synthetic biology requires interaction among biologists, physicists, synthetic chemists and computer programmers. Achieving interdisciplinarity is not a new challenge. Solutions on the supply side are likely to emerge from the efforts of education and research institutions themselves and from the effects of inter-institutional competition. However, policy might also help. For example, peer review practices bear on the way that public agencies allocate funding for multidisciplinary research. But more needs to be known about the practices adopted across research institutions, teams and departments – private and public – which enable interdisciplinary education and research. Policy makers could seek to replicate, where appropriate, the approaches of institutions that have proven successful in fostering interdisciplinary research, such as Stanford's Bio-X.

Greater interaction with industry may also be needed as the knowledge content of production rises. For example, aspects of post-graduate training could need adjustment. In the United States, current life sciences PhD level education is still focused on training for academic careers (American Society for Microbiology, 2013). However, data published in the National Science Board's (NSB's) 2014 Science and Engineering Indicators show that just 29% of newly graduated life science PhD students (2010 data) will find a full-time faculty position in the United States.

Effective systems for life-long learning and firm-level training are essential. Opportunities for skills upgrading must match the pace of technological change and ensure that retraining can be accessed when needed. Some traditional skills sets will need to be modified. For example, engineers now presented with 3D printing may need to "unlearn" parts of their classical engineering education. Overall, imparting digital skills, and skills which complement machines, is vital. Digital technology could of course also enhance skills development, for example through massive open online courses (MOOCs). The possible use of AI to tailor-make training in real time, in response to workers' specific backgrounds and the training needs, is currently being investigated.

It is also essential to ensure good generic skills – such as literacy, numeracy and problem solving – throughout the population. Strong generic skills provide a basis for learning fast-changing technology-specific skills, whatever those turn out to be in future.

Many other policy issues that affect skills systems today will continue to be important, such as establishing incentives for institutions to provide high-quality teaching. But it is not evident that emerging production technologies would raise their importance. Such issues include: establishing incentives for institutions to provide high-quality teaching; and ensuring that any barriers to women's participation in science, technology, engineering and mathematics are removed.

The next production revolution may bring changes to labour market policies

New urgency might be given to employment-related policies and institutions if changing production technologies create large labour market shocks. For example, a range of labour market policies that aim to re-employ displaced workers in mid-career might become more prominent. As the previous section noted, an important issue is whether a new generation of production technologies is likely to change the scale, frequency or character of labour market shocks. Without perfect foresight, governments should plan for a variety of scenarios, including those in which future shocks are large and arrive quickly.

While it cannot be stated with certainty how the labour market will evolve, there is reasonable conjecture on a number of likely outcomes:

- Many remaining production jobs are likely to disappear. A 2015 survey showed that 68% of British manufacturers see the potential for increasing investment in automation (Rigby, 2015).
- Self-employment could grow. Growth in self-employment has been marked in some OECD countries in recent years. For example, the number of people working for themselves in

the United Kingdom has increased by around 30% since 2010 (Dellot, 2014). Further growth in self-employment could result from push and pull factors. On the one hand, digital technologies could lower start-up costs and enable professional autonomy in many occupations. Digital platforms could also reduce information and other transaction costs in product and labour markets, which could facilitate self-employment (e.g. digital platforms can allow customers to link directly with individual producers, with firms losing their advantages as aggregators and intermediaries). On the other hand, new technologies could displace employees who then seek self-employment as the only remaining employment option. Supporting policies not directly related to production technology could be needed to accommodate rising self-employment.[9]

- There is also likely to be greater flexibility in when and where work takes place (Mokyr, Vickers and Ziebarth, 2015).

The importance of geography-specific policies could also rise

The digital economy appears to exacerbate geographic disparities in income, as it amplifies the economic and social effects of initial skill endowments (Moretti, 2012). In many OECD countries, income convergence across subnational regions has either halted, or reversed, over recent decades (Ganong and Shoag, 2015). A number of remedial policies can be considered. Investments in skills and technology are particularly important (because investments in infrastructure and transport, to facilitate the geographic spread of skills and economic benefits, while often beneficial, also have diminishing returns [Filippetti and Peyrache, 2013]). The importance of certain types of infrastructure to the location of advanced manufacturing may also grow. In particular, computer-controlled machines operating in terms of milliseconds require close proximity to Internet servers.

Policy needs long-term thinking

Statements of science, technology and industrial policy at the highest levels are frequently prefaced by the observation that the present is a time of exceptional technological change. The rapidity of current advances is also often emphasised by business leaders.[10] Expeditious action is routinely urged on policy makers because of the purported speed of technological change. While generalised assertions of accelerating change are open to question, it is the case that some technological developments that could have important impacts on production, such as in machine learning, were not foreseen just a few years ago (Domingos, 2015).

Rapid change could increase the benefits from good long-run policies and public investments. And rapid change could raise the costs of short-termism. Leaders in business, education and government must be ready to examine policy implications and prepare for developments beyond the next ten years. As a possible model, in Germany, the federal Ministry for Economic Affairs and Energy and the federal Ministry of Education and Research have created a co-ordinating body bringing together stakeholders to assess long-term strategy for Industry 4.0.

China and the next production revolution

In Chapter 12, Qian Dai examines recent and projected developments in production in China. Manufacturing is a foundation of China's economy, and China is now the largest contributor to global manufacturing value-added. China's weight in global manufacturing, combined with the country's goal of increasing the knowledge content of domestic production, has many implications for itself and for production elsewhere in the world.

Many Chinese companies have made great progress in creating and using new production technologies

Manned space flight, deep-sea submersibles, high-speed rail and the world's fastest supercomputer are all examples of China's manufacturing-related achievements. Over 2008-13, the supply of industrial robots (IRs) in China increased by about 36% per year on average. In 2013 China became the largest international market for IRs, and is expected to have some 428 000 units in 2017 (IFR, 2015). Sales of Chinese-made IRs increased 77% in 2014 (Shen, 2015). Regions traditionally strong in manufacturing mechanical and electrical products, such as the southeast provinces, have initiated large-scale programmes titled "Robots Replace Humans".

Sales of 3D printers in China increased from CNY 2 billion to CNY 3.7 billion (approximately USD 582 million) from 2013 to 2014 (Huang, 2015). And industrial 3D printing will be used for the C919, China's first domestically designed commercial aircraft (Ren, 2014).

In 2014, the IoT market in China was worth over CNY 600 billion (some USD 94 billion) (CCID Consulting, 2015). Chinese Internet companies, especially the three leading players (Baidu, Alibaba and Tencent), not only lead the market for the IoT, cloud computing and big data, they are also extending their influence to manufacturing. In December 2015 Baidu road tested a driverless vehicle. And Alibaba is promoting big-data applications in sectors ranging from robotics, the IoT and biotech, to financing and infrastructure.

China began early in nanotechnology research. In 2010-13, China ranked fourth in country-share of nanotechnology patents (OECD, 2015d). This scientific prowess has paved the way for applications of nanotechnology in industry. Biomedicine and bio-based materials are also developing rapidly. Biomedical engineering in China is seeing the fusion of biotechnology with new materials and ICT to yield new products and services (such as new artificial corneas and gene services). All of these and other achievements are associated with progress in research, education and infrastructure.

The above developments have been accompanied by a series of major policy initiatives and related public investments, the main aim of which is to advance the use of digital technologies in manufacturing. Made in China 2025, launched in 2015, is part of a 30-year strategy to strengthen China as a manufacturing power. And, more recently, the Internet Plus initiative aims to digitalise major parts of the economy. Complementary policies address a variety of cross-cutting themes: far-reaching educational initiatives, such as a national programme for teaching robotics in primary and middle schools, are under consideration at the Ministry of Education (Ren, 2016).

Upgrading manufacturing in China faces complex challenges, at home and overseas

As the population ages and labour costs surge, the cost advantage of Chinese manufacturing over the United States has fallen to less than 5% (Sirkin, Zinser and Rose, 2014). While China's labour productivity has risen over the past decade, it is still much lower than in developed countries. Global competition has intensified, and some multinational firms are moving high-end manufacturing back home.

Sizeable parts of Chinese manufacturing experience shortcomings in management and digital capability. China still relies heavily on imports for advanced manufacturing.

Challenges exist not only in increasing government investment in science and innovation, but also in commercialising research, improving infrastructures, making markets work more efficiently, and encouraging private sector innovation (e.g. over 70% of nanotechnology patents, and 50% of robotics patents, are filed by the academic and public sectors [World Intellectual Property Organization, 2015]). And environmental concerns have become more prominent as air, water and soil pollution from manufacturing has worsened.

Policy also needs to cope with a range of related developments, such as labour market disruption and the growing importance of cyber security. The Robots Replace Humans programmes result from a lack of labour and rising wages in eastern China and are not expected to negatively impact the labour market (Bai, 2014). But technological change is raising demand for multi-skilled managers, researchers and technicians. And new labour market policies are needed as entrepreneurship and self-employment are set to increase. The average number of detected information security incidents in China over the 12 months before December 2015 reached 1 245, a 417% rise compared to the previous year (PwC, 2015). As ICT becomes critical to key industries, information security will need strengthening.

The next production revolution and global value chains (GVCs)

Recent decades have seen growing international integration of markets for capital, intermediate inputs, final goods, services and people. The increased partitioning of production in GVCs has drawn policy makers' attention to the economic consequences of occupying different parts of a GVC (OECD, 2013). GVCs are constantly evolving. Recent OECD work finds little evidence at this time of the reshoring of manufacturing from emerging to advanced economies as the result of automation, cost-saving technological change or other conditions (de Backer et al., 2016). However, evidence suggests that European companies which intensively use robots are less likely to locate production abroad. Features of some technologies, such as 3D printing, could lead to some production being brought closer to developed-country markets. And rapid developments in China, as noted above, are likely to shape developments globally.

Successful absorption of new technologies in developing countries could help to achieve productivity, structural transformation and environmental goals. Indeed, some new production technologies are well suited to economic conditions in many developing countries. For example, certain state-of-the-art robots are relatively inexpensive and do not require highly skilled operators. And low-cost drones could make some agricultural processes more efficient. With improved channels of knowledge diffusion, such as the Internet, opportunities for technological "leapfrogging" could arise, particularly in large developing economies. But learning to use new technologies is clearly a challenge for companies in many developing economies. Comin and Mestieri (2013) examined how long it takes technologies to be adopted in developed and developing economies, and how intensely those technologies are then used. For 25 technologies, the authors find converging rates of adoption across countries, but divergence in the intensity of use.

Opportunities and risks in GVCs are likely to be industry-specific

Labour-intensive industries which predominate in many developing countries, such as garments, shoes and leather, furniture, textiles and food, could be less susceptible to change, since many processes in these industries are not yet fully (or economically) automated. Other industries, such as the electrical and electronics and machinery sectors, are likely to be significantly affected, particularly if wages are growing, because of their high potential for automation. In other sectors, such as automotive manufacture, adopting new production technologies is expected to be determined not so much by wages or the potential for automation, but by domestic demand and consumers' growing desire for quality and customisation.

But technological change could quickly threaten capacity in developing countries. For example, because of dexterity requirements, footwear manufacture has to date been labour-intensive. But Adidas recently built a shoe manufacturing facility in Germany which is fully automated, permits significant customisation, and takes just five hours for a full production cycle, compared to the current norm of several weeks (Shotter and Whipp, 2016).

Many developing countries will need to upgrade entire production systems. A challenge for firms in developing countries will be their ability to upgrade the machines, factories and ICT systems required for interconnected production. The machines and ICT systems of firms in many developing countries are out of date, and difficult to retrofit with new technologies. Emerging production technologies operate with tolerances, technical standards and protocols with which developing-country firms are often unfamiliar. And such technologies usually require an uninterrupted source of power, which is not available in some developing countries.

Investments in new technologies can also require a range of complementary expenditures. Investing in robots, for example, usually entails spending of similar size on peripherals (such as safety barriers and sensors) and system implementation (such as project management, programming, installation and software). Financing such investments can require a range of financing institutions, from venture capital firms to development banks, machinery-related term lending, and specialised SME and start-up lending. Such a breadth and depth of financial services is only available in a few developing countries.

As discussed earlier in this chapter, the next production revolution requires well-functioning tertiary-level institutions able to educate students in science, technology, engineering and mathematics (STEM) disciplines, as well as a close integration between production and vocational training institutes. But these are the most resource and investment-intensive areas of education, and as such have not been traditional priorities in developing countries.

As Chapter 2 describes, fully benefiting from the next production revolution requires comprehensive, reliable, secure high bandwidth telecommunications infrastructure. Providing coverage to rural areas, particularly in large countries, will facilitate communication between local producers and consumers and the development of integrated domestic markets. Fast connectivity to facilitate rapid data interchange is likely to be a hallmark of future production, and one of its success factors. Developing the required infrastructures is a further challenge for many developing countries.

Conclusion

This report examines the economic and policy implications of a set of technologies which are significantly changing production. The changes to come could be at least as far-reaching as past transformations. As these technologies transform production, they will have far-reaching consequences for productivity, employment, skills, income distribution, trade, well-being and the environment. All of these technologies are evolving rapidly.

Companies, economies and societies require that governments understand how production could develop and how policies and institutions should respond.

The policy issues examined in this report are many, but not exhaustive. Other areas of policy also matter. For example, as machines engage in markets in increasingly autonomous ways, competition policy could shape and be shaped by developments in AI. Significant growth of 3D printing could raise trade policy concerns (with respect e.g. to the levying of border taxes as data transit rather than goods). And consumer policy might have to tackle new issues, e.g. with respect to the safety of wearables linked to the IoT.

Many issues raised in this report require more assessment. A key question concerns the distributional implications of technological change. New production technology will make it possible for many to live richer and better lives. But, as discussed earlier, these technologies could also worsen income inequality. Responding to the distributional effects of new production technologies requires policies beyond the domains of science and innovation.[11] But it should be recalled that technology-driven growth might lower wealth inequality (as contrasted with income inequality) if the growth spurred by technology exceeds the growth in returns to innovation-intensive capital. As stressed recently by Piketty (2014), a rate of growth which exceeds the rate of return to capital might favour a fall in wealth inequality.

System fragility might be another subject for deeper analysis. As production systems become more complex and ICT-mediated, the risk and consequences of possible cascading vulnerabilities could increase. Critical interlinked ICT systems might behave in unpredictable and emergent ways (in fact, interacting algorithms were involved in the "Flash Crash" of May 2010, when more than USD 1 trillion in value were lost in minutes from global stock markets). As digital production systems proliferate, the ability to anticipate failures in technology could also diminish (Arbesman, 2016). Improved understanding of complex systems is essential if governments are to protect society from potentially serious disruptions (Nesse, 2014).

A further priority in policy-relevant research has also been pointed to by Tassey (2014), and is apparent in many chapters of this report. This relates to the need for better understanding of how government action affects the production function for advanced technologies. Specifically, more detailed evidence is required on the effects of private and public choices to allocate R&D resources across industries, phases of the R&D cycle, across different tiers in high-tech value chains and through different types of research infrastructure. Better policies entail a need to shift from a focus on the scale of resources dedicated to the next production revolution, with more attention given to the effect of the composition of support across policies, programmes and institutions.

Notes

1. See *www.extremetech.com/electronics/185960-foxconn-is-attempting-to-replace-its-human-workers-with-thousands-of-robots*.
2. E.g. non-routine cognitive tasks are often performed by workers in professional, technical and managerial jobs. Non-routine manual tasks – requiring personal interaction, visual and language recognition and situational adaptability – are regularly performed, for example, by janitors, personal care assistants and drivers (Autor, Levy and Murnane, 2003).
3. Employment is more likely to grow after technology shocks in firms operating in industries with low inventory costs, elastic demand and flexible prices (Chang, Hornstein and Sarte, 2009).
4. Many jobs were also created for computer, automated teller and office machine repairers (The Economist, 2011).

5. See Professor Hod Lipson at *www.youtube.com/watch?v=tmPLeQLdfPA*.
6. In a related way, research on experts' assessments of innovative ideas also underlines the value of multiple viewpoints. Examining raw ideas and market outcomes, Kornish and Ulrich (2014) show that consumer panels are a better way to determine a "good" idea than are ratings by leading experts in the industry concerned.
7. See: *http://spectrum.ieee.org/semiconductors/materials/germs-that-build-circuits*.
8. More generally, an often-cited concern is whether the transformative growth in computing power which has underpinned the digital revolution will continue. With many digital devices, processing speeds, memory capacities, sensor density and accuracy, and even numbers of pixels, are linked to Moore's Law, and exhibit similar exponential improvements. But atomic-level phenomena limit the extent to which transistors on integrated circuits can be shrunk. Some experts believe a lower bound might be reached in the early 2020s (power consumption has already reached a limit). It is unclear how the end of Moore's Law – and possible offsetting innovations in such areas as new algorithms and three-dimensional integrated circuits – might affect the pace and direction of technological change.
9. E.g. as regards regulations which affect home-based work.
10. In many public pronouncements Google's Director of Engineering, Ray Kurzweil, has stressed that aspects of technological development, particularly in ICT, will accelerate exponentially.
11. But the relevant measures could be many: from a basic income guarantee for every adult, variants of which are being trialled in a number of countries, to earned income tax credits, and the provision of resources for lifetime learning and job retraining.

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