Meeting of the OECD Council at Ministerial Level

Paris, 1-2 June 2016

ENABLING THE NEXT PRODUCTION REVOLUTION: THE FUTURE OF MANUFACTURING AND SERVICES - INTERIM REPORT

OECD
BETTER POLICIES FOR BETTER LIVES

Enabling the Next Production Revolution: the Future of Manufacturing and Services - Interim Report

TABLE OF CONTENTS

EXECUTIVE SUMMARY

1. The next production revolution (NPR) entails a confluence of technologies ranging from a variety of digital technologies (e.g. 3D printing, Internet of Things, advanced robotics) to new materials (e.g. bio- or nano-based) to new processes (e.g. data driven production, artificial intelligence, synthetic biology). These technologies will be available in the near future. As these technologies have an impact on the production and the distribution of goods and services, they will have far-reaching consequences for productivity, skills, income distribution, well-being and the environment.

2. This interim report seeks to provide background to a wider discussion on productivity and change in OECD economies. Its intent is to sketch the opportunities, risks and economic and policy ramifications of a set of technologies which are likely to be important for production over the near term (to 2030). This focus on technologies affords the opportunity for thinking about technology-specific policies. It also permits tractability.

3. As an interim report, this document leaves a number of issues only partially addressed. More work is being undertaken, for instance, on the specific design characteristics of institutions for technology diffusion.[1] And beyond this current 2-year project, still broader themes need to be addressed, such as why aggregate productivity is still slowing, despite the advent of these new technologies. Nevertheless, this report provides a broad view of the issues and policy challenges raised by the production revolution that is now underway.

Key messages

4. **The technologies considered in this report, from ICTs and robots to new materials, have more to contribute to productivity than they currently do.** Often, their use is predominantly in larger firms. And even in larger firms, many potential applications are underused. Unexploited opportunities exist throughout manufacturing. This may be particularly the case with the cluster of technologies that make up the NPR – digital, material and process – that are combinatorial and as such interact in ways that are hard to assess.

5. While **new technologies will create jobs through many direct and indirect channels, and productivity-raising technologies will benefit firms and the economy overall**, the associated adjustments could be significant. Hardship could affect many if rapid labour displacement were to occur in a major sector, or in many sectors simultaneously. Policymakers need to monitor and actively manage the labour market adjustments.

6. Compared to earlier industrial revolutions, induced by steam and electrification, the spread of inventions that can transform production will transpire over a shorter time period. But **it could take considerable time for new technologies, once invented, to diffuse throughout the economy and for their productivity effects to be fully realised**. Moreover, the duration of this period is uncertain. The past has seen unrealistic enthusiasm regarding timescales for the delivery of a number of production technologies.

7. **Diffusion of the technologies must include not only the hardware**, but also the complementary investments and know-how needed to fully exploit the technologies, ranging from skills to new forms of business organisation, especially for SMEs. Here, the efficient deployment and reallocation of human and

---

[1] Table 1 provides examples of such institutions.

financial resources will be essential, as is the creation of an environment which fosters business dynamism. Aligning framework policies that promote product market competition, reduce rigidities in labour markets, remove disincentives for firm exit and barriers to growth for successful firms is critical. New firms will introduce many of the new production technologies.

8. **Effective institutions dedicated to technology diffusion will also be necessary.** Some of these institutions, such as technical extension services (which provide information and outreach, especially for SMEs), tend to receive low priority in the overall set of innovation support measures. But there is evidence that they can be effective, if well designed (for instance, manufacturing extension services, which provide outreach, often to small firms, have been carefully evaluated).

9. **Data is at the centre of many of the NPR technologies and need to be treated as a new infrastructure for 21st century production.** Policy mixes are needed that encourage investments in data that have positive spillovers across industries, obstacles to the reuse and sharing of data should be examined carefully, and coherent data governance frameworks should be developed.

10. Rapid technological change could challenge **the adequacy of skills and training systems**. Some new production technologies raise the importance of inter-disciplinary education and research. Greater interaction between education and training institutions is often needed, and this need may grow as the knowledge content of production rises. Ensuring good digital and generic skills – such as literacy, numeracy and problem-solving – throughout the population will be important.

11. **Public understanding and acceptance** of new production technologies is crucial. Policymakers and institutions need to be realistic about what can be expected from technology. Hyperbole is too frequent. Science advice should be demonstrated to be unbiased and trustworthy. And public deliberation is essential for building mutual understanding between scientific communities and the public.

12. Better anticipating trends through technology foresight could assist policy and the allocation of research funds. **Foresight processes can bring benefits in themselves, such as strengthened stakeholder networks.** They can also encourage policy co-ordination and organisational innovation and help direct **sound policies for science and R&D**. Many of the technologies covered in this report have arisen because of advances in scientific knowledge and instrumentation emanating from both the public and private sectors.

13. **Sound science and R&D policies are also essential.** For instance, synthetic biology, new materials and nanotechnology have all arisen because of advances in scientific knowledge and instrumentation, while basic knowledge of artificial intelligence has been elaborated over decades in academic research before surfacing recently in a business context. Among other things, policy must support basic science, inter-disciplinary research, research interaction with industry and the efficient commercialisation of research.

14. **Long-term thinking is essential.** Leaders in business, education, unions and government must be ready to examine policy implications and prepare for developments beyond typical election cycles. A long-term perspective on policy also requires **reflection on how policy priorities might need to evolve**, for instance as a consequence of technological change itself. For example, **major challenges to the intellectual property system** could come from the emerging ability of machines to create (at least one machine-derived invention has already been patented).

15. While NPR will present a challenge to developed countries, it could be especially challenging for emerging and developing countries. New production technologies could erode the low wage advantage of some developing economies, leading to shifts in global value chains. Development models predicated on

successive stages of industrialisation may be challenged and the gap between the technologically advanced countries and the rest could grow. But this scenario might be mitigated by several factors including rapidly declining costs of many of these technologies, more efficient channels of knowledge diffusion, and improved regulations, laws and standards across countries. More work is needed to better analyse this issue, but the NPR project will provide relevant insights from recent developments in People's Republic of China (hereafter: 'China').

Conclusion

16. The more governments understand how production could develop in the near future, the better placed they will be to prepare for the risks and reap the benefits. The NPR raises multiple complex policy challenges and will require adjustment to a wide range of public policies to reap its full benefits. But through judicious policy, the opportunity exists to influence the next production revolution now. Final result from the NPR project will be available in early 2017.

INTRODUCTION

1. This paper is an interim report on the OECD cross-cutting project "Enabling the Next Production Revolution". This project is being implemented over the 2015-2016 biennium. This paper is a condensed version of the paper DSTI/IND/STP/ICCP(2016)1 – *The Next Production Revolution: An Interim Project Report* – which was presented to the Committee for Scientific and Technological Policy (CSTP) at its March 14-15 meeting, and to the Committee on Industry, Innovation and Entrepreneurship (CIIE) at its March 7-8 meeting.[2]

2. The Directorate for Science, Technology and Innovation (STI) is leading the work, with inputs also provided by the Environment Directorate (ENV) and the Office of the Secretary-General's (OSG) Strategic Foresight team.

The NPR project has a technological focus

3. In different ways, many policy, institutional and broader conditions (or mega-trends) will shape the future of production. These range from environmental conditions, to demographics, to the fact that production will increasingly take place across borders, in global value chains (OECD, 2013*a*). To do justice to all of the above influences on production is barely feasible in a single study. Accordingly, the NPR project aims to explore the economic and policy ramifications of a set of technologies which are likely to be important for production over the near term. This focus on technologies affords the opportunity for thinking about technology-specific policies. A technological focus also permits tractability. Accordingly, the project's overall aims are to:

- Explore – and inform governments of – possible science and technology-driven developments in selected production technologies over the next 10-15 years;
- Outline the risks and opportunities that could be created by such changes. These risks and opportunities relate to the economy, society, well-being and the environment;
- Examine policies that could help to cope with risks and realise the opportunities; and,
- Assess how policymakers prepare for the future and what best-practice constitutes.

4. The backdrop to this project is one in which major science and technology-driven changes in the production and distribution of goods and services are already occurring. Others – possibly more significant still - are on the horizon. Such changes could have far-reaching impacts on productivity, income distribution, well-being and the environment. These impacts are likely to vary across industries, countries and sections of the workforce. As well as positive impacts, some possible technological developments in production also entail risks (recently, for example, innovation has displaced entire industries, such as chemical-based photography). The more completely governments understand how production might develop, the better placed they will be to prepare for the risks and reap the benefits. Indeed, a number of

2 Overarching policy themes addressed in connection with new production technologies were outlined in DSTI/IND/STP/ICCP(2015)8/REV1 – *Enabling the Next Production Revolution* - which was submitted to the Ministerial Council Meeting on 3-4 June 2015, as a background document.

OECD governments and think-tanks have recently prepared, or are preparing, reports on the future of production, many with a focus on manufacturing.[3]

Many technological changes will affect production and distribution over the next 10-15 years

5. The range of technologies that could significantly affect production and distribution is great. Technologies can complement each other in many ways. Today, for instance, new software and advances in data science help to develop new materials. And new materials might soon replace silicon semiconductors with better-performing substrates, allowing more powerful software applications in turn. This combinatorial nature of technology implies that foresight is always tenuous. Indeed, retrospective analysis shows that predictions about technological timelines tend to be particularly inaccurate (Armstrong *et al* 2014). Nevertheless, many potentially disruptive production technologies are on the horizon. Underpinned in particular by advances in various dimensions of digital technology, new production technologies will often be smaller, faster, more accurate, less expensive, more ubiquitous and more reliable than the technologies they supersede. A small sampling, examined in this project, include:

- Powerful data analytics, and large data sets, which increasingly permit machine functionalities that rival human performance in tasks, such as pattern recognition, where humans were long thought to possess a permanent advantage over machines.

- Robots, which are set to become more intelligent, autonomous and agile.

- An increased connectedness of parts, components and machines to the Internet.

- Synthetic biology, which among other applications could allow petroleum-based products to be manufactured from sugar-based microbes, and which could bring the life sciences closer to engineering.

- 3D printing, which already permits printing of complex objects (such as an electric battery) that embody multiple structures made from different materials.

- Nanotechnology, through which new properties are being imparted to materials, making them stronger, lighter, more electrically conductive, more sieve-like, and so on.

Risks will also attend technological change in production

6. Risks will arise with technological change in production. The various risks will have higher or lower probabilities, and more or less significance, for different countries and population groups. For instance:

- The effect of technological change on employment and earnings inequality has recently drawn increased attention from academics and policymakers.

---

3 For instance, in the United States, in July 2012, the Advanced Manufacturing Partnership Steering Committee, working within the framework of the President's Council of Advisors on Science and Technology (PCAST), outlined recommendations for positioning the United States for long-term leadership in advanced manufacturing. Similarly, in 2013 the United Kingdom's Government Office for Science produced 'The Future of Manufacturing: A New Era of Opportunity and Challenge for the UK'.

- Policymakers in some countries fear the consequences of unpreparedness in the face of rapid technological change. 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 undermine labour-cost advantages on which many emerging economies rely.

- As production systems become more complex and ICT-mediated, the risk and consequences of system fragility may increase (Nesse, 2014).

- Risks also exist that potentially beneficial technological advances might be held back by a lack of public understanding or social acceptance.

- And innovations might create new hazards that need to be countered. For instance, some nano-particles might have harmful effects on health. And ICTs allow ever more scientific information to be available to ever larger numbers of people, with some of this information – such as genetic information - being potentially dangerous.

7. A key focus of the NPR project is the productivity effect of new production technologies. A main message is that much unexploited potential for productivity growth exists. Well-designed policies could help to realise the opportunities for productivity growth and broaden the productive base. A number of other cross-cutting policy considerations arise ranging from issues of technology diffusion, to intellectual property concerns, to the practice of foresight. In addition, some among the many technology-specific lessons from the ongoing work are the following:

- Two trends mean that digital technologies are transformational for production: (i) their falling cost, which has allowed wider diffusion; and, most importantly, (ii) the combination of different ICTs, and their convergence with other technologies. Data-driven innovation is transforming all sectors of the economy and digital technology is also making industry more services-like. Cloud computing and the Internet of Things (IoT), among other technologies, will bring radical change. Advanced robotics semantically linked by data from across the factory floor offer vast improvements in functionality and flexibility and are now becoming common in other settings such as health care. The pervasive nature of digital technology raises many policy challenges. For instance, coherent data governance frameworks are needed, barriers to ICT diffusion, interoperability and standards should be lowered, and complex and sometimes new issues of liability, competition, privacy and consumer protection need well-designed regulations and effective implementing institutions.

- The tools also exist today to begin a **bio-based revolution in production**. Bio-based batteries, artificial photosynthesis and micro-organisms that produce biofuels are just some among recent breakthroughs. Governments can assist the development of sustainable supply chains for bio-based production and help resolve technical and economic questions about production, often through public-private partnerships. Governments can also lower barriers to trade in bio-based products, lower regulatory hurdles that hinder investment, and support the necessary inter-disciplinary science and education.

- **Nanotechnology** can enable many areas of production. Nanotechnology needs international collaboration, as many of the research and engineering tools are hard to gather in a single institute (or even region). Policymakers should develop multidisciplinary networks and support innovation and commercialisation in small companies. Timely and clear guidelines are needed for assessing the risk of nanotechnology-enabled products, as is international coherence in this area. Since 2006, the OECD has led international efforts to harmonise regulatory approaches to the safety of nanotechnology enabled products.

- **3D printing** includes a group of technologies and processes that use a digital file to build a physical three-dimensional object using additive manufacturing. 3D printing could augment manufacturing productivity, although today the technology is most economical for small quantities of complex customised products. 3D printing has potential environmental benefits. To achieve these, policy should encourage low-energy printing processes and low-impact materials. Governments can: target grants or investments to commercialise research in these directions; remove intellectual property barriers to enable 3D printing of repair parts for legacy products (for instance, washing machines no longer in production); and, support certification of 3D-printer sustainability.

- Recent advances in scientific instrumentation, data science and computation have contributed to a revolution in **materials science**. Industrial materials will have properties not seen before. Increasingly, the desired properties will be deliberately designed into materials. Policies are needed to facilitate open data and open science (for instance for sharing simulations of materials structures). Progress on new materials requires close collaboration between industry, universities, research funding agencies and public laboratories. And, again, steps are needed to foster interdisciplinary research and education.

8. The remainder of this paper is structured as follows. Chapter 1 addresses the themes of productivity, work and the next production revolution. Chapter 2 examines the role of digital technologies in future production. Chapter 3 considers bio-production and industrial biotechnology. Chapter 4 focuses on nanotechnology as an enabler of future production. Chapter 5 assesses the impacts of 3D printing on manufacturing and the environment. Chapter 6 considers developments relating to new materials. Chapter 7 reviews how governments can help to foster the diffusion of new production technologies. Chapter 8 considers the influence of public acceptance on the adoption of new technologies and the options which are open to government. Chapter 9 examines what governments can do to develop foresight about future production. Chapter 10 discusses cross-cutting policy considerations. And Chapter 11 summarises the next steps in the NPR project. Each chapter summarizes possible directions for government policy.

9. The Secretariat is working to prepare a final publication, for release in early 2017. As the project progresses, various themes will be examined in more detail than has been possible for this interim report. For instance, more attention will be given to the specific design characteristics of institutions for technology diffusion.

1. Productivity and the technologies of the next production revolution

1.1 Productivity and the technologies of the next production revolution

10. A fundamental relationship exists between innovation and long-term productivity. Today, raising rates of economic growth is a priority for most OECD governments. Over the longer-term, shrinking working-age populations, combined with natural resource constraints, mean that the future of growth in OECD economies will increasingly depend on productivity-raising innovation [see *The Productivity Inclusiveness Nexus* - C/MIN(2016)3].

11. Many OECD economies have experienced faltering productivity growth in recent years. Some high-profile commentators have claimed that slower productivity reflects a general innovation hiatus. These voices come from academia and from industry. Techno-pessimists hold, among other things, that innovation will slow because the cost of innovation rises as technology advances. In contrast, techno-

optimists variously argue that new digital and other technologies will raise productivity (Brynjolfsson and McAfee, 2013), and that economic history suggests that technological progress could even accelerate (Mokyr, 2014). Techno-optimists also highlight that official measures of economic growth understate progress. For instance, national statistical offices usually collect no information on the use of mobile apps, or online tax preparation, or business spending on databases (Mandel, 2012), while the consumer surplus created by thousands of new digital products is absent from official data.

Emerging technologies affect productivity through many channels.

12. Emerging production technologies will affect productivity through mechanisms that are many and varied. For instance:

- 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;
- The combination of new sensors and actuators, big data analysis, cloud computing and the Internet of Things is enabling autonomous productivity-enhancing machines and intelligent systems;
- Automated maintenance scheduling, enabled by new sensors, artificial intelligence and machine-to-machine communications, will reduce disruptions to production caused by breakdowns;
- The mix of industrial biotechnology with state-of-the-art chemistry can increase the efficiency of bioprocesses (most biological processes have low yields);
- 3D printing can remove the need for assembly in some stages of production by printing already-assembled mechanisms;
- Progress in materials science and computation will permit a simulation-driven approach to developing new materials. This will reduce time and cost as companies perform less repetitive analysis;
- 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.

Box 1. How large are the productivity effects?

Evidence on productivity impacts from new production technologies come mainly from firm and technology-specific studies. A sample of these studies is given here. These studies suggest sizeable potential productivity impacts. However, the studies follow variety of methodological approaches, and often report results from a few, early-adopting technology users, making aggregate estimates difficult to derive:

- 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 ICTs (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 - would increase labour productivity by 14% on average, but with significant cross-industry variations (Barua et al., 2013).
- The Internet of Things reduces costs among industrial adopters by 18% on average (Vodatafone, 2015).
- Autonomous mine haulage trucks could in some cases increase output by 15-20%, lower fuel consumption by 10-15% 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).
- By raising productivity the new technologies can also improve financial performance among adopters. A case study commissioned for the NPR project shows that, by developing a significant IoT and data analytics capability, a leading United States automaker has saved around USD 2 billion over the past 5 years (2011-2014 and most of 2015). 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).

But there is much unexploited potential for productivity growth…

13. The technologies considered in this report have more to contribute to productivity than they currently do (Box 1). Often, their use is predominantly in larger firms. Even in larger firms, many potential applications are underused, which can reflect such factors as skills constraints, the novelty of the technologies, incomplete understanding of a technology's potential uses, and institutional inertia. Unexploited opportunities exist throughout industry. For instance, robotics could improve logistics and reduce the price of food and other goods by several percent (CCA/CCR, 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).

…and it could take considerable time for the productivity gains from new technologies to be realised.

14. The past has seen unrealistic enthusiasm regarding timescales for the delivery of some industrial technologies. Sometimes, as with nanotechnology, this partly reflected miscalculation of the technical challenges. In terms of adoption, advanced ICTs remain below potential. Cloud computing, for instance, was first commercialised in the 1990s, but has still only been adopted by less than one in four businesses in OECD countries. And the mere availability of a technology is not a sufficient condition for its uptake and successful use. Realising the benefits of a technology often requires that it be bundled with investments in complementary assets such as new skills and organisational forms and that new, better adapted business models are invented that channel income to innovators (OECD, 2013b).

1.2 Work, automation and the new technologies of production

15. Among the general public, senior policy figures and business leaders, growing concerns have recently been voiced regarding the employment implications of digital technologies. For instance, 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). A recent survey of technology experts in the United States found that 48% were concerned that digital technologies will lead to widespread unemployment (PEW, 2014). Fears also exist that digital technologies could alter the nature of labour markets – for instance through the growth of a crowd-sourced workforce - to the detriment of workers.

Progress in computing is leading to novel machine capabilities…

16. Since the period of manual computing, and depending on the standard used, the cost of computer calculation has fallen by 1.7 trillion to 76 trillion-fold. Most of this decline 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).

…and an increased scope and rate of automation

17. The routine tasks of most operatives in manufacturing are now automated. Cargo-handling vehicles and forklift trucks are increasingly computerized. 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). Software can generate complex and novel industrial designs. The *Quill* programme writes business and analytic reports. Computer-based managers are being trialled. Recent softwares can accurately interpret some human emotions, presaging new forms of machine-human interaction (Khatchadourian, 2015). And autonomous vehicles might soon substitute for large numbers of commercial drivers.

Automation has advanced most in tasks more easily defined in computer code, contributing to employment polarisation

18. In recent decades, in OECD labour markets, the share of employment in high- and low-wage jobs has increased, 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 (i.e. tasks are those which are more easily described by computer code) (Goos and Manning, 2007; Acemoglu, 2002). Because manual tasks in many services occupations are less susceptible to description in code, automation has also contributed to a shift in employment from middle-income manufacturing to low-income services (Autor and Dorn, 2013).

But new technologies create jobs through many channels

19. A technology-driven increase in productivity benefits the economy through one or more of the following channels: lower output prices, higher workers' wages, or higher profits. Lower prices raise real incomes among consumers. This increases demand for other goods. And higher workers' wages raise demand and job creation in other markets. Even if productivity gains only lead to higher profits, or shareholders and workers save their increased income, the wider economy still benefits (Miller and Atkinson, 2013). The higher profits are distributed to shareholders, who spend all or part of this new income, adding to aggregate demand. And increased savings among shareholders and workers lowers interest rates and raises investment, eventually creating jobs. Jobs will also arise in firms that make new forms of production equipment and machinery. The key issue is two-fold: 1) a temporal one of the relative speed of displacement versus the creation of new work and the length and depth of the adjustment period; and 2) the relative nature of the jobs (e.g. skills, wages) created as opposed to those being displaced.

Productivity-raising technologies benefit the economy

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

- Investments in ICT had no net effect on labour demand in 19 OECD economies between 1990 and 2012 [DSTI/ICCP/IIS(2014)6]. A permanent fall in the cost of ICT capital reduced labour demand per unit of output, but increased output by the same proportion.

- 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: 23.7% of all employment in 1871, to 8.3% in 2011. It also saw a shift to jobs requiring caring and empathy: 1.1% of all employment in 1871 to 12.2% in 2011. Routine jobs suffered most.

In firms and industries, the employment effects of technological change are also generally positive

21. Evidence at the level of firms and industries mostly shows that productivity-enhancing technology causes job losses in some cases and job gains in others (Miller and Atkinson, 2013). But the number of firms and industries which experience employment growth exceeds the number in which employment contracts. 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).

But adjustment can be painful

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

23. Hardship could affect many if rapid labour displacement were to occur in a major sector, or in a number of sectors simultaneously. The technology of driverless vehicles could present such a case. Taken together, just over 3 million people work as commercial drivers in 15 European Union countries. Suddenly eliminating the need for drivers could create an extraordinary labour market shock. However, the likelihood of major simultaneous technological advances in many sectors is low (Miller and Atkinson, 2015). And even in a single sector, projecting the employment effects of new technology is not always straightforward. For instance, driverless cars might not substitute for the work performed by all human drivers. Many delivery drivers must interact with customers in ways that today's machines cannot (Markoff, 2015a).

While new technologies bring jobs, specifying what or where they will be is problematic

24. 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. New

technologies can also affect employment in very indirect and unexpected ways, hindering foresight. For instance, Toyota has decided to put human workers back into manufacturing after realising that craftsmen also play a role in improving production processes, which robots do not (Markoff, 2015b).

Limits currently exist on the extent of automation

25. While automation is advancing quickly, challenges also exist in enlarging the scope of machine substitution for workers. 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 (Davis and Marcus, 2015).

Policymakers need to monitor and prepare for adjustment processes

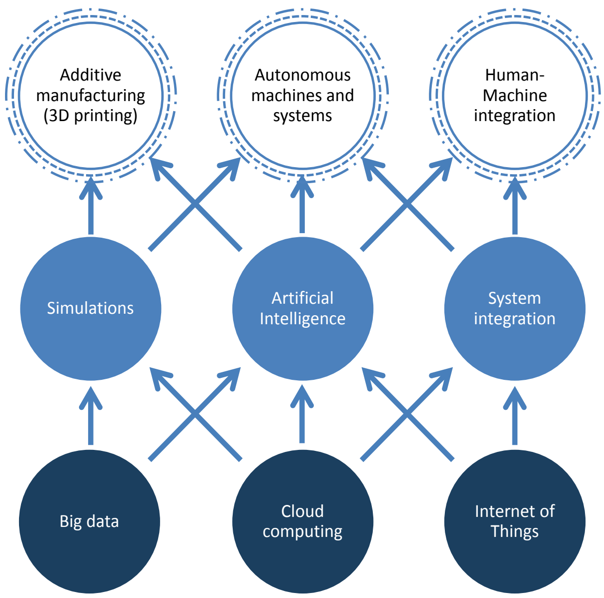
26. This section has highlighted the historical evidence that productivity-raising technologies lead to labour market adjustments at higher levels of income. It has also underscored that such adjustment might be highly disruptive, while the precise pace and scale of inevitable future adjustments are unknown. It may be that 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. Policymakers need to monitor and prepare for such possibilities.

2. Digital technologies and future production

The confluence of different technologies is driving the digital transformation of industrial production

27. Two trends make digital technologies transformational for production: (i) their falling cost, which has allowed wider diffusion; and, most importantly, (ii) the combination of different ICTs, and their convergence with other technologies (thanks in particular to embedded software and the IoT). In a highly stylised way, figure 1 depicts the key ICTs which are enabling the digital transformation of industrial processes.

Figure 1. The confluence of key technologies enabling the industrial digital transformation



28. The technologies at the bottom of figure 1 enable those on top, as indicated by the arrows. The technologies at the top of figure 1 - including additive manufacturing (3D printing), autonomous machines and systems, and human-machine integration - are the applications through which the main productivity effects in industry are likely to unfold. The use of the above technologies in industry has been described variously as "Industrie 4.0", the "Industrial Internet", and "network manufacturing". A common characteristic of these technologies is the intensive use of data to optimise the processes.

Data-driven innovation (DDI) is transforming all sectors of the economy

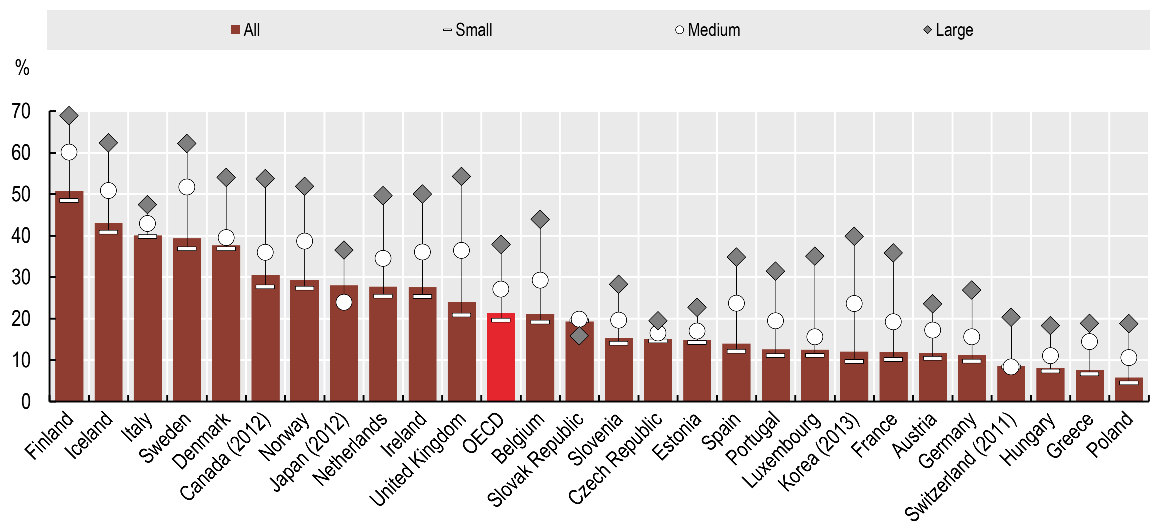
29. The term 'big data' refers to data characterised by their volume, velocity (the speed at which they are generated, accessed, processed and analysed) and variety (such as unstructured and structured data). Big data promises to significantly improve products, processes, organisational methods and markets, a phenomenon referred to as data-driven innovation (DDI). Firm-level studies suggest that using DDI can raise labour productivity by approximately 5-10%, relative to non-users (OECD, 2015a). DDI will impact on production and productivity in services, manufacturing and agriculture.

Cloud computing enhances agility, scalability and interoperability

30. Cloud computing allows computing resources to be accessed in a flexible on-demand way with low management effort. Many high-potential industrial applications of ICTs, such as autonomous machines and systems, and complex simulation, are very computationally intensive and require supercomputers. Especially for start-ups and SMEs, cloud computing has increased the availability, capacity and affordability of computing resources. But significant variation exists across countries and firms in the adoption of cloud computing (Figure 2). There is also large variation in use by size of business, with larger enterprises more likely to use cloud computing.

Figure 2. Enterprises using cloud computing services by employment size class, 2014

As a percentage of enterprises in each employment size class



Note: Data for Canada refer to the use of "software as a service", a subcategory of cloud computing services.

Source: OECD Science, Technology and Industry Scoreboard 2015. Based on data from Eurostat, Information Society Statistics and Statistics Canada.

The Internet of Things (IoT) will bring radical change

31. The term 'Internet of Things' (IoT) refers to the connection of devices and objects to the Internet. Thanks to new sensors and actuators, and in combination with big data analysis and cloud computing, the IoT enables autonomous machines and intelligent systems. The IoT can bring improved process efficiencies, customer service, speed of decision-making, consistency of delivery and transparency/predictability of costs (Vodatafone, 2015). The IoT will also bring major economic and social benefits not directly related to production, for instance in health and in vehicle efficiency.

Box 2. ICT policy considerations - data as a new infrastructure for 21st century production

Governments should develop an innovation policy mix that encourages investments in data that have positive spillovers across industries while addressing the low appropriation of returns to data sharing. The combination of intellectual property rights (IPR), licences and alternative incentive mechanisms such as data citations, data donation or philanthropy need to be considered further.

Obstacles to the reuse and sharing of data should be examined carefully. Non-discriminatory access regimes, including data commons or open access regimes, should be explored.

Coherent data governance frameworks should be developed. Access to data should not necessarily be free or unregulated. A balance is needed between openness (and the social benefits from access to and the reuse of data), and the legitimate concerns of those whose privacy and IPRs may be negatively affected.

Data and digital services are increasingly traded and used across sectors and national borders. And digital technology is also making industry more services-like.

32. The digitisation of industry is having an impact on the nature of business models and the organisation of production. In the 1980s, Rolls Royce began selling "power by the hour", a development made possible by ICTs and the data being derived that allowed the firm to offer a range of maintenance and support services. Today the IoT allows manufacturing companies to monitor the actual use of their goods and thus provide customised *pay-as-you-go* services. These services are priced based on real-time operating data. Manufacturers of energy production equipment, for instance, increasingly use sensor data to help customers optimise complex project planning.

33. As data becomes an essential factor for business, companies increasingly divide their digital processes – hosting, storage and processing – across many countries. Countries are highly interdependent in terms of data flows. Countries which are home to major providers of digital services are likely to also be major destinations for cross-border data flows (from which those digital services are constructed). Conversely, countries which host major users of ICT-related services are often major sources of the data underpinning those services.

Barriers to ICT diffusion, interoperability and standards should be lowered

34. The digitalisation of production requires the diffusion and use of key ICTs. However, many businesses, and in particular SMEs, lag in adopting ICTs. For instance, the adoption of supply chain management, enterprise resource planning (ERP), and radio frequency identification (RFID) applications by firms is still much below that of broadband networks or websites. But it is these advanced ICTs that enable digitalised industrial production.

35. An important aspect of interoperability for the Internet-of-Things is identification and numbering policies. An issue that warrants special attention by governments and regulators is the liberalisation of

access to IMSI (international mobile subscriber identity) 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.

Box 3. ICT policy considerations - diffusion, interoperability and standards

Governments need to act if regulatory barriers are preventing adoption. For instance, liberalising access to IMSI numbers has enabled Enexis, a Dutch energy network, to deploy 500 000 SIM cards (not tied to a mobile operator) to its smart meters.

Barriers to Internet openness legitimate or otherwise, can limit the inter-operability of data-driven services in particular in economies where deployment of data-driven services is poor due to failures in ICT infrastructure markets. Barriers to Internet openness can be the result of business practices or government policies. They may also have a legal basis, such as the protection of privacy and IPRs, as well as a security rationale.

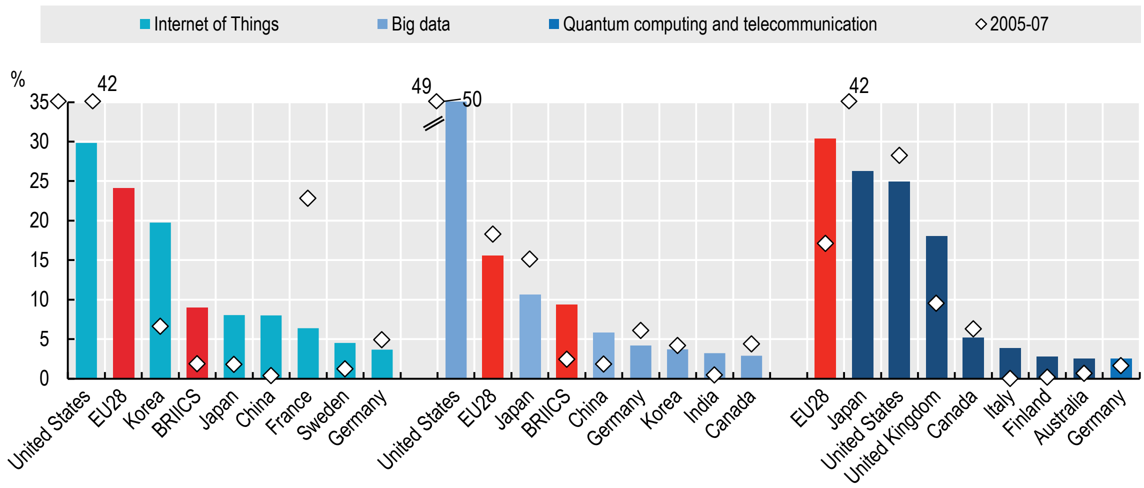
The increasing role of software in production gives intellectual property rights (IPRs) - in particular copyright - strategic importance. A key IPR concern relates to application programming interfaces (APIs). APIs allow applications to interact. Promoting open standards in APIs would boost interoperability and reuse of data and digital services, while enhancing competition among service providers.

The digitalisation of industrial production requires research and development in fields such as the IoT, data analytics and computing

36. Countries with greater research capabilities in the IoT, data analytics and computing could enjoy first-mover advantages from the digitalisation of industry. Currently, invention of DDI-related technologies is concentrated in only a few economies (figure 3), suggesting the possible emergence of a data-driven digital divide.

Figure 3. Leaders in IoT, big data and quantum computing technologies, 2005-07 and 2010-12

Share of IP5 patent families filed at USPTO and EPO, selected ICT technologies



Source: OECD Science, Technology and Industry Scoreboard 2015. OECD calculations based on IPO (2014), Eight Great Technologies: the Patent Landscapes and STI Micro-data Lab: Intellectual Property Database, June 2015.

Liability, transparency, and ownership

37. Data analytics leads to new ways of making decisions. This can raise productivity. But for various reasons, intentional and unintentional, data-driven and AI-enabled decision making can also produce mistakes. For example, unforeseen behaviours in algorithmic trading systems have sometimes led to significant financial losses, such as Knight Capital Group's loss of USD 440 million in 2012. The risk of erroneous decisions raises questions of how to assign liability between decision-makers, the providers of data and ICTs (including software).

Privacy, consumer protection, competition law and taxation – new challenges to regulation.

38. New ICTs could raise serious concerns relating to privacy, consumer protection, competition and taxation. Existing regulatory frameworks may be ill-suited for some of the new challenges.

Box 4. ICT policy considerations - privacy, liability and competition

Policymakers need to acknowledge that transparency requirements may extend to the processes and algorithms underlying automated decisions. These transparency requirements could come into tension with existing intellectual property rights and the processes and algorithms at the core of certain business' operations.

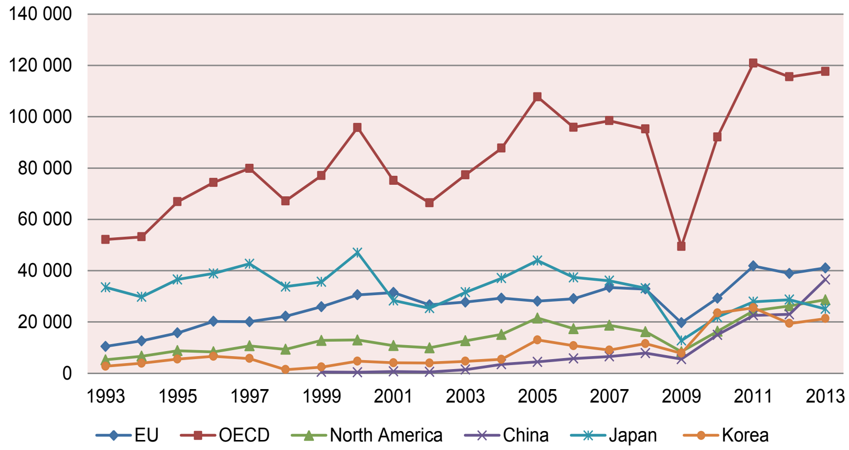
Governments need to address privacy concerns. Comprehensive data collection enabled by the IoT can erode privacy. Promoting privacy-enhancing technologies and the empowerment of individuals through more transparent data processing, and data portability, via such initiatives as MesInfos (France), should be considered.

Digital technologies also underpin the development of robotics

39. Robots first entered industry – initially in the automotive sector - in the 1960s. For decades, industrial robots were large, expensive, operated from static positions indoors, and performed one or a small number of repetitive and sometimes hazardous tasks, such as welding and machining. But a convergence of digital and other technologies has yielded a second generation of robots. These are smaller, less expensive, more autonomous, more flexible and cooperative. They can be programmed and used by average workers. Kuka, for instance, makes autonomous robots that collaborate and automatically adjust their actions to fit the next unfinished product (Lorentz et al, 2015). Some robots even perform tasks by imitating workers. Robots also have new roles in services. For instance, using minimally invasive robots, several thousand prostate operations a year are performed in the United States. This allows shorter admission periods, fewer infections and faster recovery (CCC/CRA, 2009).

40. In 17 OECD countries, from 1993 to 2007, the number of robots in industry increased by over 150%. The market for personal and household service robots is growing by about 20 percent a year, and prices are expected to decline quickly in the near future (MGI, 2013).

Figure 4. Global Sales of Industrial Robots, 1993-2013



Source: IFR Statistical Department at World Robotics: www.worldrobotics.org

41. Robot utilisation varies greatly across countries: 48% of Spanish firms and 44% of Danish firms used at least on industrial robot in 2009, compared to just 23% of firms in the Netherlands (Fraunhofer, 2015).

42. More intelligent and autonomous robots will come about through improvements currently being seen in: computing performance; electromechanical design tools and numerically controlled manufacturing; electrical energy storage and electronics power efficiency; the availability and performance of local wireless digital communications; the scale and performance of the Internet; and, global data storage and computational power (Pratt, 2015). Challenges remain, particularly in perception (recognising specific objects in cluttered environments), manipulation and cognition.

43. The next generation of miniaturised, complex products with short life-cycles will require a level of assembly adaptability, precision and reliability which exceeds human capabilities (CCC/CRA, 2009). And as OECD populations age, robots will help to relieve demographic constraints on production. As well as increasing process reliability, robots reduce lead times for finished manufactured goods, allowing greater responsiveness to changes in retail demand. European manufacturers that use robots are more efficient than non-users. And such robot users are less likely to relocate production outside Europe (Fraunhofer, 2015).

44. Robot use increases strongly with firm size. In Europe, 36% of surveyed companies with 50 to 249 employees use industrial robots, compared to 74% of companies with 1000 or more employees (Fraunhofer, 2015). This size-sensitivity reflects the greater financial resources, experience with advanced production technologies, and economies of scale available to larger firms.

3. Bio-production and industrial biotechnology

45. Petro-chemistry dramatically changed production in the early twentieth century. Several decades of research in biology have now yielded synthetic biology (see Box 5 for definitions) and gene editing technologies. When allied to modern genomics - the information base of all modern life sciences - the tools are in place to begin a bio-based revolution. Bio-based batteries and materials, artificial photosynthesis and micro-organisms that produce biofuels are just some among recent breakthroughs (OECD, 2016a forthcoming).

46. Everyday chemicals and fuels represent the largest market for bio-based products. In the last few years the technology to produce entirely non-natural chemicals has been proven (Yim et al., 2011). This technology is now being commercialised.

Box 5. What are these technologies?

Genomics: is a discipline that applies recombinant DNA, DNA sequencing methods, and bioinformatics to sequence, assemble, and analyse the function and structure of genomes. In many ways it is an information technology – the code is not digital but genetic.

Industrial biotechnology: involves the production of goods from sustainable biomass instead of finite fossil-based reserves. The biomass can be wood, food crops, non-food crops or even domestic waste.

Synthetic biology: aims to design and engineer biologically-based parts, novel devices and systems as well as the redesigning of existing, natural biological systems.

47. Industrial biotechnology could improve the productivity and competitiveness of the OECD chemicals sector by improving environmental performance. Biotechnology also offers unique solutions to dependence on oil and petrochemicals. For example, a hugely demanding task is to create food crops that make their own fertilizer, through synthetic biology and, in the near future, gene editing (Keasling, 2015). If achieved, this outcome would help to de-link agriculture from the fossil-fuel based fertilizer industry.

Bio-based products are starting to become cost-competitive

48. Bio-based materials and fuels currently suffer in competition with the fossil-based industry. Over decades, oil and gas supply chains and production processes have been perfected. The production plants are mature and completely amortised, and the economies of scale achieved mean that fossil-based industries produce many products at low cost. Furthermore, fossil fuel subsidies are vast.

49. For bio-based products, none of these conditions exist. Investing in bio-based manufacturing - the most potent symbol of which is the integrated bio-refinery - has been a major risk: the early products have not been price-competitive, markets have had to be created by government, and supply chains – particularly the collection of biomass - are far from perfected. However, nascent bio-based manufacturing is bringing new products to market. Indeed, almost one hundred bio-based chemicals are close to commercialisation (E4Tech, 2014).

Box 6. Bio-production 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 also 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 et al., 2015). And currently there are no environmental performance standards for bio-based materials.

Global sustainable biomass governance is a patchwork of many voluntary standards and regulations. Biomass disputes are already occurring and threaten to create international trade barriers.

One of the greatest challenges in bio-based production is its multi-disciplinarity. Research and training will have to create not only the new technologies required, but also a cadre of technical specialists (Delebeque and Philp, 2015). There are some proven ways for governments to tackle this challenge, such as by organising research degrees with a focus on business, not academic, outcomes. To create a non-research workforce, modern apprenticeships would be another mechanism.

A priority in support for research should be synthetic biology and metabolic engineering approaches to reducing the innovation cycle time of industrial biotechnology. It takes about 7.4 years for a synthetic biology company to get a bio-based chemical to market (Lux Research, 2015). Targeted research could help bring products to market on a shorter timescale.

Governments should focus on three objectives as regards regulations: to boost the use of instruments, in particular standards, so as to reduce barriers to trade in bio-based products; to address regulatory hurdles that hinder investments; and, to establish a level playing field for bio-based products with biofuels and bioenergy (Philp, 2015). Governments could also ensure that waste regulations are less proscriptive and more flexible, enabling the use of agricultural and forestry residues and domestic wastes in bio-refineries.

4. Nanotechnology – an enabler to the next production revolution

50. The term 'nano' describes a unit prefix (i.e. 1 nm = 1 x 10^{-9}m. A sheet of paper is about 100,000 nm thick). The widest definitions of nanotechnology include all phenomena and processes occurring at a length scale of 1 nm – 100 nm. The power and versatility of nanotechnology stem from the ability to control matter on a scale where the shape and size of assemblies of individual atoms determine the properties and functions of all materials and systems, including those of living organisms. The command of materials on the nanometre-scale can enable innovation in all existing industrial sectors. As it develops, nanotechnology will enter a widening range of uses and require complementary technologies and institutions.

51. In the 1980s, science- and technology-foresight studies envisaged rapid advancements in nanotechnology. Progress in the science and its application, however, has been significantly slower than expected. Progress has been slowed by the high cost of research and development instrumentation, as well as by failures to scale-up from laboratory-scale procedures to industrial manufacture. The difficulty of achieving commercial-scale production was largely due to inadequate understanding of the relevant physical and chemical processes, and the inability to control production parameters at that scale.

52. However, over the last 10 years techniques for large-scale production of nanotechnology-based materials have improved significantly. Nanotechnology is increasingly used in production processes and manufactured products. For instance, nanotechnology can enable the replacement of 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).

Box 7. Nanotechnology - main policy considerations

Nanotechnology requires increased efforts in international collaboration. The suite of research and engineering tools needed for a comprehensive nanotechnology R&D infrastructure is hard to gather in a single institute. Nanotechnology research requires international collaboration to achieve its full potential. Publicly funded R&D programmes should allow the involvement of academia and industry (large and small companies) from other countries.

Support is needed for innovation and commercialisation in small companies. The high cost of nanotechnology R&D is a limitation for many small companies. Policy makers could seek to improve SMEs' access to equipment by: (a) increasing the amount of money SMEs get in research grants; (b) subsidising/waving the service fee; or (c) providing SMEs with vouchers for equipment use.

Regulatory uncertainties regarding risk-assessment and approval of nanotechnology-enabled products must be addressed. Products awaiting market entry are sometimes shelved for years before a regulatory decision is made. Policies should support the development of transparent and timely guidelines for assessing the risk of nanotechnology-enabled products, while also striving for international coherence. Since 2006, the OECD has led international efforts to improve regulatory approaches to the safety of nanotechnology enabled products.

5. 3D printing, production and the environment

53. 3D printing is expanding rapidly owing to falling printer and materials prices, the rising quality of completed objects, and innovation. The global 3D printing market is projected to grow at around 20% a year from 2014 to 2020 (Markets and Markets, 2014).

54. Recent innovations permit 3D printing with novel materials - such as glass and metals - as well as printing of 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.

3D printing and the future of manufacturing

55. 3D printing could augment productivity in a number of ways. For instance, 3D printing of already-assembled mechanisms is possible, which could reduce the number of steps in some production processes. And design processes can be shortened, owing to rapid prototyping (Gibson *et al*., 2015). Objects can also be printed which are otherwise impossible to manufacture (such as metal components contained within other closed and seamless metal components). Currently, most 3D printing is used to produce prototypes, models and tools, with only 15% producing parts in sold goods (Beyer, 2014).

56. 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 instance, Boeing has already 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 total manufacturing sales.

57. Expansion of 3D printing into other industries 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 (MGI, 2013), although it remains difficult to predict precisely how fast this technology will be deployed. Furthermore, the cost of switching is not linear. 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.

3D printing and the environment

58. The NPR project has examined the environmental effects of 3D printing relative to two important industrial technologies: machining and injection moulding. These were chosen to 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.

Common misconceptions exist about the environmental effects of 3D printing

59. Two of the most 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.

3D printing's potential for enhancing environmental sustainability is high

60. 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; and,
- It can allow fewer chemical ingredients to yield more variation in material properties by varying printing processes;

61. 3D-printed parts can also lower the environmental impacts of some products because of how the products can be used, even if environmental impacts during manufacturing are high. This can happen in two ways: (i) by printing replacement parts for legacy products that would otherwise be discarded; and (ii) by reducing weight in a vehicle or otherwise improving a product's energy efficiency (G.E.'s lighter 3D-printed parts for a jet engine improved fuel efficiency by 15% (Beyer, 2014)).

Box 8. Additive manufacturing 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). Another way in which printers can minimise material impacts is by using compostable biomaterials with high print quality. Printer design and operation can also reduce waste by minimising the use of support material (printers of all kinds often use support materials in addition to the actual modelling material to prevent part warping before they are fully formed). The support material can also differ from the model material.by producing hollow parts, and by avoiding failed prints. Policy mechanisms to achieve these priorities should include:

- Targeting financial grants or investments (either existing programs or new funds) to commercialising research in these directions;
- Removing intellectual property barriers to enable 3D printing of repair parts for legacy products that lack existing supply chains. For example, a consumer may realise a washing machine is broken and that it only requires a small hinge to be fixed. Theoretically, a consumer with a 3D printer could go to a computer, find the appropriate 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 programs by governments and other large institutions.

6. New materials and the next production revolution

62. Advances in scientific instrumentation, such as atomic-force microscopes and X-ray synchrotrons, 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, such as 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).

The era of trial and error in materials development is coming to an end

63. 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 (for instance, the possibility exists that silicon in integrated circuits could be replaced by materials with superior electrical properties). In the next production revolution, engineers will concurrently design the product and its constituent materials (Teresko, 2008).

64. 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.

New materials matter for productivity and competitiveness

65. A simulation-driven approach to materials development will reduce time and cost as companies perform less repetitive analysis. Simulation will also permit better products, such as stronger complex structures. Successful integration of materials modelling and data sciences into decision support for product development can also shorten the time between materials discovery and their commercial use. The Accelerated Insertion of Materials program, run by the United States' Defense Advanced Research Project's Agency (DARPA), has demonstrated such time savings. Large companies, too, will increasingly compete in the development of materials. This is because a proprietary manufacturing process applied to proprietary materials creates long-term competitive differentiation (*The Economist*, 2015).

Box 9. New materials and the next production revolution - main policy considerations

New materials will raise new policy issues and give new emphases to long-standing policy concerns. For instance, 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 science-industry interface. For instance, well-designed policies are needed for open data and open science (for sharing simulations of materials structures, or for sharing experimental data in return for access to modelling tools, for example (Nature, 2013)).

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 manufacture must understand materials modelling and theory, while modellers and theorists must understand the challenges faced in industry (MGI, 2014).

7. The diffusion of new production technologies – what can governments do?

A key question is how to ensure that new technologies, ideas and business practices diffuse in OECD economies

66. A critical issue is how already-developed technologies diffuse. Small firms, for instance, tend to use key technologies less frequently than larger firms. For instance, in Europe, 36% of surveyed companies with 50 to 249 employees use industrial robots, compared to 74% of companies with 1000 or more employees (Fraunhofer, 2015).

67. OECD (2015b) analysis has identified several factors that shape the diffusion process at national and international levels: (i) global connections via trade, FDI, participation in GVCs and the international mobility of skilled labour; (ii) connections and knowledge exchange within the national economy, such as the interaction between scientific and higher education institutions and businesses; (iii) the scope that exists for experimentation by firms – especially entrants – with new technologies and business models; (iv) the extent of complementary investments in R&D, skills, organisational know-how (i.e. managerial capabilities) and other forms of knowledge-based capital. If firms which could lead the next production revolution are unable to attract the human and financial resources to grow, the future development of technology and its diffusion will be stunted.

Inefficient resource reallocation can have many causes

68. The causes of inefficient resource reallocation can be many, including a lack of product competition, rigid labour markets, disincentives for firm exit, barriers to growth for successful firms, and policy conditions such as restrictions on trade. For example, the sensitivity of capital investment to a change 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).

Learning from the global frontier is a particular challenge for developing and emerging economies

69. Comin and Mestieri (2013) examined how long it takes technologies to be adopted in developed and developing economies, and how intensely those technologies are used. For 25 technologies, the authors find a convergence in adoption rates across countries, but divergence in the intensity of use. Learning how to use new technologies is still a challenge for companies in many developing economies. Conditions which facilitate such learning include open trade, efficient skills allocation, managerial quality, the volume of business R&D, and the capacity of governments to develop and implement e-government services (McGowan *et al.*, (2015).

Beyond framework conditions, it is important to design effective institutions for technology diffusion

70. Institutions for technology diffusion are intermediaries, structures and routines that facilitate the adoption and use of knowledge, methods and technical means. Some of the institutions involved, such as technical extension services, tend to receive low priority in the standard set of innovation support measures. But there is evidence that they can be effective, if well designed.

71. The conventional 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 experience high transaction costs in trying to diffuse technologies; and finance for scale-up and implementation is not always forthcoming. Support from technology diffusion institutions seeks to guide and support enterprise capabilities, adoption, and justify 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 become even more important, to aid potential users to sift through burgeoning amounts of information and to support decision making in the context of rapidly changing technologies and expertise requirements.

72. Innovation systems invariably contain multiple sources of technology diffusion, such as universities and professional societies. Table 1 offers an initial typology.

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

73. 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. An example is the United States National Network for Manufacturing Innovation (NNMI). The NNMI uses private non-profit organisations as the hub of a network of company and university organisations to develop standards and prototypes in areas such as 3D printing and digital manufacturing and design.

Digital information technologies are being deployed to facilitate diffusion

74. 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 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 gaps for activities between research and commercialisation, and comparable gaps in the capacity for commercialisation of research

75. For example, the Innovation Corps (I-Corps) programme was established by the United States 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 program enhances the knowledge of participants and their capacity to start companies around NSF-funded research (Weilerstein, 2014).

Policies have also placed greater emphasis on demand for new production technologies

76. Attention to the procurement of innovation by government agencies has grown across many countries, often targeted to SMEs. Incentives such as R&D tax credits, regulations and standards are also 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.

Table 1. Initial typology of institutions for technology diffusion

Type	Operational mode (primary)	Example
Dedicated field services	Diagnostics, guidance and mentoring	Manufacturing Extension Partnerships (United States); German Industrial Collective Research for SMEs.
Technology-oriented business services	Advice linked with finance Capacity development	Industrial Research Assistance Program (Canada); I-Corps (United States)
Technology transfer offices	Intellectual property licensing	University TTOs (multiple countries)
Applied technology centres	Contract research	Fraunhofer Institutes (Germany), TNO (Netherlands)
Technology information exchange	Technology community networking	Knowledge Transfer Networks (United Kingdom)

Demand-based behavioural change	Knowledge transfer incentives	Innovation vouchers (multiple countries)
Technology partnerships	Collaborative applied research Prototyping and standards	National Network for Manufacturing Innovation (United States)
Open source sharing	Open source sharing Virtual networks	Registry of Standard Biological Parts (United States)

Box 10. The diffusion of new production technologies - main policy considerations

Technology diffusion institutions need realistic goals and time horizons. Many new technologies are introduced into existing ecosystems where sunk costs have been invested in old ways of doing things. For example, fully automated factories proposed in the 1980s failed in part due to the difficulty of integrating existing supply chains with newly shortened product life cycles. Introducing new ways to integrate and diffuse technology takes time, patience and experimentation. Yet many governments want visible results quickly, without risk.

Misalignment can exist between the stated aims of technology diffusion institutions and their operational realities. While some new 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 current technologies to their fullest extent and lack absorptive capabilities for sophisticated technologies. In such cases, pragmatic approaches to technology diffusion may be needed, coupled with long-term relationships that build capabilities for more advanced strategies.

Policymaking needs better evidence and a readiness to experiment. A better understanding of effective organisational designs and practices for technology diffusion is vital. There is more to this than re-designing assessment and evaluation, and fostering knowledge about good practices, although these are important. More fundamentally, existing institutions need to be able to discover new approaches, to embed innovative methods in their operations and be well integrated into innovation systems.

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.

8. Public acceptance and new technologies – why does this matter and what options are open to government?

77. 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 sound rationale for adoption, and where large investments have been made (EC 2013). 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, political protests often halted their use (Winner 1986).

78. Public pressure can feed into regulatory choices that condition the adoption of technology. For instance, in the area of biotechnology, public controversies over genetically modified organisms (GMOs) have had a major impact on regulation and approvals of new crops in Europe (Watson and Preedy 2016).

While public concerns can constrain technology, they can also lead to increased safety and acceptability

79. Scientific studies and environmental protest in the 1960s and 1970s led to stricter regulation of pesticides and other chemicals (Davis, 2014). Regulation can also enable technology adoption by stipulating the terms of acceptable use: activism in the 1960s about the safety of automobiles led to higher safety requirements and shaped the development of the automobile industry (Packer, 2008).

Biotechnology has been the subject of persistent public conflicts over societal risks

80. In both developed and developing countries, genetically modified crops have raised concerns around health and safety risks, the capacity to contain and reverse their release, and the effects of intellectual property on concentration in the structure of the agro-food industry (Jasanoff 2005). Such concerns have been resolved differently in different countries. Stark 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 WTO (Pollack and Shaffer 2009). Governments will have to anticipate public concerns around the most recent biotechnological advances, especially gene editing (Box 11).

Box 11. Gene editing in society

With so-called "gene editing" techniques, especially those using the CRISPR-Cas9 system (named as by the journal *Science* as the Breakthrough of 2015), scientists are now able to change a DNA sequence at precise locations on a chromosome. Gene editing will make the design and construction of organisms with desired traits easier and cheaper. It raises the possibility, for example, of new methods for the control of pests and diseases as well as improvements in plant and animal breeding. Recently, CRISPR has been used in China to edit genomes of non-viable human embryos. Similar experiments have been approved in the United Kingdom (Callaway 2016).

In March 2015, a group of scientists and ethicists, including Nobel laureates David Baltimore of Caltech and Paul Berg of Stanford, proposed a worldwide moratorium on altering the genome to produce changes that could be passed on to future generations. In December 2015, the National Academies of Science in the United States, along with the Chinese Academy of Sciences and the United Kingdom's Royal Society convened an international summit of experts from around the world to discuss the scientific, ethical and governance issues associated with human gene-editing research (Reardon 2015).

Other technologies addressed in this report have raised public concerns of different kinds.

81. Some concerns have to do with risk, such as how nano-technologies might affect human health (recent OECD work has found significant knowledge gaps with respect to the final disposal of nanoparticles (OECD, 2016b)). Government programmes to collect and leverage big data have also raised significant public concerns and ethical issues. For instance, 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 (Kirby 2014). And the next production revolution could raise societal issues not seen before. For instance, as machine autonomy develops, who will be responsible for the outcomes that machines give rise to, and how will control be exercised?

Box 12. 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. An emphasis on short-term benefits can lead to disappointment (Nuffield Council 2012). 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. 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 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 put resources into making systems of expertise more robust by encouraging more exchange with publics, encouraging clear communication about sources of uncertainty, and 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, science funders in many OECD countries have sought to integrate attention to ethics, legal and social issues. The planners of the Human Genome Project (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 the budget to the ethical, legal and social implications of research. Since this pioneering approach, 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 Europe's Horizon 2020 programme and the United States 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 halls have been pioneered in Denmark and elsewhere for a broad range of emerging technologies relevant to the NPR. Deliberation can 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, so these might feed into the process.

9. Developing foresight about future production: what should governments do?

82. Greater foresight in science and technology is sought by most governments. For instance, a goal of the America Competes Act 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 the future and shaping it

83. Foresight processes aim to systematically and transparently identify and assess social, technological, economic, environmental and policy conditions that shape some aspect of the future. Foresight processes are: (i) action-oriented; (ii) participatory (often involving researchers, business people, policy-makers and representatives of citizen groups); and, (iii) consider multiple futures.

84. Prediction is not the primary role of foresight exercises. In developing roadmaps and examining projections, foresight assists preparation for multiple possible futures. In addition, process benefits arise from doing foresight.

Foresight can – and should – take many forms, varying in thematic coverage, geographic scope, focus, methods and time horizons

85. Several foresight exercises have focused on manufacturing and production, including "Making Value for America: Embracing the Future of Manufacturing, Technology, and Work" (2015), "The Future of Manufacturing: A new era of opportunity and challenge for the UK" (2013), and "Manufacturing Visions – integrating diverse perspectives into pan-European foresight (ManVis)" (2003-2006).

Foresight can aid thinking about multiple possible futures

86. Governments can easily be trapped by the need to deal with the short-term. Foresight provides space for longer-term thinking. Foresight also explores different possible futures. In uncertain times, thinking in terms of multiple future states is a pre-condition for devising policies to cope with unexpected

developments. Furthermore, in a complex world, many phenomena cannot be understood in isolation. They must be seen in context, from a number of viewpoints. Foresight involving participatory methods can incorporate necessarily diverse perspectives.

Foresight can facilitate the mobilisation and alignment of stakeholders

87. 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 both horizontally (i.e. across policy domains, or between parliament and government) and vertically (i.e. between ministries and executive agencies).

And foresight can help to reframe policy issues and spur organisational innovation

88. Government bodies tend to be organised along the lines of rigidly demarcated policy domains. Organisational structures can lag 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 (for example, in shifting from S&T-led research to societal challenges-driven research). Government bodies can also be insular, with the same participants sometimes repeatedly involved in decision-making. Foresight processes have the potential to enlarge and renew the framing of policy issues. In a connected way, foresight can also induce organisational innovations.

10. Cross-cutting policy considerations

The range of relevant policy issues is broad, which highlights the need for policy coordination

89. The range of policy issues relevant to a next production revolution is extremely broad. Evidently, production is affected by many types of policy, from those on skills and training, to policies affecting domestic and international competition, to tax codes that affect investments in machinery and software, to policies which influence the efficiency of judicial systems and the effectiveness of bankruptcy laws, to policies on infrastructure and financial services. In addition, this paper has pointed to the roles of a 'meso' level of policy, such as the design of particular institutions and programmes. The breadth of relevant policy issues underscores that some forms of policy coordination may be needed.

Sound science and R&D policies are essential

90. The technologies covered in this report result from science. Synthetic biology, new materials and nanotechnology, among others, have arisen because of advances in scientific knowledge and instrumentation. Many policy choices determine the strength of science and research systems and their impacts on production. Policymakers need to be attentive to such matters as: the procedures for allocating funds for public research; the balance between support for applied and basic research; a variety of institutional features and incentives which shape 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.

Governments must create an environment which fosters business dynamism

91. OECD research over recent years has highlighted the role of new and young firms in net job creation and in nurturing radical innovation. New firms will introduce many of the new production technologies. But Criscuolo, *et al*. (2014), find declining start-up rates across a wide range of OECD countries since the early 2000s. Governments must attend to a number of conditions which affect this dynamism. These conditions have been treated in detail in other OECD analyses (for instance, Calvino, Criscuolo and Menon (2016) and Andrews, Criscuolo and Menon (2014)).

Technological change is raising new challenges for the intellectual property (IP) system - notably the patent system - and raising questions around some of the system's basic assumptions.

92. One major challenge to the IP system comes from the emerging ability of machines to "create", an ability which until now was restricted to humans. For example, KnIT, a machine learning tool developed by IBM, successfully identified kinases with specific properties among a set of known kinases. Those properties were then tested experimentally. In other words, the specific properties of those molecules were discovered by software, and patents were filed for the inventions. A second challenge stems from the ability to digitalise physical objects. 3D printing, for instance, might 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. The future of these technologies could be affected by how IP and patent systems adapt. Governments need to ensure the suitability of IP rules in the context of rapidly changing technologies.

Distribution rather than scarcity will be a primary concern

93. The distributional effects of new production technologies require policies beyond the domains of science and innovation. The possible measures are many, from earned income tax credits to the provision of resources for lifetime learning and job retraining. Tackling an uneven distribution of skills is 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).

Education and skills systems will need constant attention

94. Rapid technological change could challenge the adequacy of skills and training systems to match demand and supply for new skills (although digital technology could of course play a role in augmenting skills supply, for instance through Massive Open Online Courses). For some production technologies, current skills supply is insufficient. Improving the efficiency of skills matching in labour markets supports productivity (McGowan and Andrews, 2015).

Some new production technologies raise the importance of inter-disciplinary education and research

95. Many of the technologies examined in this report require more interdisciplinary education and research. The increasing complexity of some scientific equipment also demands the use of multiple skill types. But some education systems and individual institutions may not be responding as well as is needed.

96. Achieving inter-disciplinarity is not a new challenge. But more needs to be known about the practices adopted across research institutions, teams and departments - private and public – which enable inter-disciplinary education and research. Policymakers could seek to replicate, where appropriate, the approaches of institutions successful in fostering inter-disciplinary research, such as Stanford's Bio-X.

Greater interaction with industry is needed, and this need may grow as the knowledge content of production rises

97. Aspects of postgraduate training may 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 PhDs (2010 data) will find a full-time faculty position in the United States.

Developing a high level of generic skills throughout the population will also be important

98. Generic skills such as literacy, numeracy and problem-solving provide a foundation for the acquisition of technology-specific skills (whatever those technology-specific skills turn out to be in future). Good generic skills help to 'future proof' human capital.

99. Many other policy issues that affect skills systems today will continue to be important, but it is not evident that a next production revolution would *raise* their importance. Such issues include: establishing incentives for institutions to provide high-quality teaching; supporting firm-level training and life-long learning; and, ensuring that any barriers to women's participation in science, technology, engineering and mathematics are removed.

NPR may bring changes to labour market policies too

100. New urgency might be given to employment-related policies and institutions if changing production technologies create large labour market shocks. For instance, a range of labour market policies that aim to re-employ displaced workers in mid-career might also become more prominent. One 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 scenarios in which future shocks are large and arrive quickly, such as could occur if the remaining technical obstacles to self-driving vehicles were quickly overcome.

Policymakers need to engage in long-term thinking

101. More public discussion is needed of the policy implications of the new production technologies. Leaders in business, education and government must be ready to examine policy implications and prepare for developments beyond the next ten years (for instance with respect to progress in machine learning). 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 coordinating body bringing together stakeholders to assess long-term strategy for Industry 4.0 ("Plattform Industrie 4.0").

A long-term perspective on policy also requires reflection on how policy priorities might evolve

102. Even best-practice policy today may need to change over time. This could happen because of dynamics inherent to the technologies concerned, or because of wider social or economic trends. Policy makers need to ask 'are new policy priorities likely to emerge?'. For instance, major challenges to the intellectual property system could come from the emerging ability of machines to create, an ability which until now was restricted to humans (at least one machine-derived invention has already been patented). Similarly, 3D printing might also create complications in connection with patent eligibility. For instance, if 3D-printed human tissue improves upon natural human tissue, it may be eligible for patenting, even though naturally-occurring human tissue is not.

The next production revolution is likely to affect the future location of production in global value chains, but exactly how is uncertain

103. Over recent decades, the world has witnessed a growing international integration of markets for capital, intermediate inputs, final goods, services and people. The increased partitioning of production in global value chains (GVCs) has drawn attention to the economic consequences of occupying different stages in a GVC (OECD, 2013a). There is as yet little evidence that GVCs are shifting due to the current wave of technological change. However, GVCs are constantly evolving (OECD, 2015c). Recent OECD work finds little evidence at this time of the reshoring of activities from emerging to advanced economies as the result of automation, cost-saving technological change and other conditions (De Backer, *et al*., 2014). However, evidence presented earlier in this paper does show that European companies which intensively use robots are less likely to locate production abroad. In addition, the NPR project is examining developments in production in China. Aside from the fact that China accounted for 20.8% of global manufacturing output in 2013, China's goal of increasing the knowledge content of domestic production will expand the range of markets in which China competes and will also contribute to the development of production technologies in those markets.

104. While NPR will present a challenge to developed countries, it could be especially challenging for emerging and developing countries. As the technologies lead to a realignment of relative costs and the development of new business models, the low wage advantage of some countries may be off-set, leading to a shift in global value chains. Development models predicated on successive stages of industrialisation may be challenged and the gap between the technologically advanced countries and the rest may grow. However, this scenario could be mitigated by several factors, including rapidly declining costs of many technologies and improved channels of knowledge diffusion, such as the Internet, which may allow some countries to leap-frog to more advanced stages of development in some sectors. This prospect merits further study.

11. Next steps in the NPR project

105. Simultaneously, the Secretariat is working to prepare a final publication. At present, chapters on the following themes are planned (in addition to an overall synthesis): ICT, big-data and production; biotechnology and future production; nanotechnology and future production; new materials and future production; 3D printing and its environmental impacts; public acceptance and future production; how should governments use foresight?; supporting advanced manufacturing production in the United States; diffusing production technologies – what can governments do?; connecting manufacturing with research – what can governments do?; and, skills and the next production revolution.

106. As the project progresses, various themes will be examined in more detail than has been possible for this interim report. For instance, more attention will be given to the specific design characteristics of institutions for technology diffusion. Further consideration will likewise be given to how new production technologies could affect countries' positions in global value chains. New proposed projects on the "Future of Work" and the "Digitalisation of the Economy and Society" will further examine many of these policy issues.

BIBLIOGRAPHY

Acemoglu, D. (2002), "Technical Change, Inequality, and the Labor Market", Journal of Economic Literature 40(1), pp.7-72.

American Society for Microbiology (2013), "Microbe-powered jobs: how microbiologists can help build the bioeconomy". Report on an American Academy of Microbiology Colloquium Dallas, TX // February 2013.

Andrews, D., C. Criscuolo and C. Menon (2014), "Do Resources Flow to Patenting Firms?: Cross-Country Evidence from Firm Level Data", OECD Economics Department Working Papers, No. 1127, OECD Publishing, Paris. DOI: http://dx.doi.org/10.1787/5jz2lpmk0gs6-en

Armstrong, S., K.Sotala and S.S.ÓhÉigeartaigh (2014), "The errors, insights and lessons of famous AI predictions – and what they mean for the future", Journal of Experimental and Theoretical Artificial Intelligence, 26:3, pp.317-342, DOI:10.1080/0952813X.2014.895105.

Autor, D.H. and D.Dorn (2013), "The Growth of Low-Skill Service Jobs and the Polarization of the US Labor Market", American Economic review, 103(5), pp.1553-97.

Barua, A., D. Mani, R. Mukherjee (2013), "Impacts of effective data on business innovation and growth", Chapter Two of a three-part study, University of Texas at Austin, www.businesswire.com/news/home/20100927005388/en/Sybase-University-Texas-Study-Reveals-Incremental-Improvement, accessed 20 May 2015.

Basu, S., J.L.Fernald and M.S.Kimball (2006), "Are Technology Improvements Contractionary?", American Economic Review, Volume 96, 5, pp. 1418-1448.

Beyer, C. (2014), "Expert View: Strategic Implications of Current Trends in Additive Manufacturing", *Journal of Manufacturing Science and Engineering*, Vol. 136, pp. 064701–1.

Bosch, R., M. van de Pol and J. Philp (2015), "Define biomass sustainability". Nature 523, 526-527.

Brynjolfsson, E., L.M. Hitt and H.H. Kim (2011), "Strength in Numbers: How Does Data-Driven Decisionmaking Affect Firm Performance?", Social Science Research Network (SSRN), 22 April, http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1819486.

Callaway, E. (2016), "UK Scientists Gain Licence to Edit Genes in Human Embryos." *Nature* 530 (7588): 18–18. doi:10.1038/nature.2016.19270.

Calvino, F., C. Criscuolo, and C. Menon (2016), "No Country for Young Firms? Start-up Dynamics and National Policies". OECD Science, Technology and Industry Policy Paper, forthcoming.

CCA/CRA (2009), "Roadmap for US Robotics : From Internet to Robotics", http://www.us-robotics.us/reports/CCC%20Report.pdf

Chang, Y., A.Hornstein and P-D.Sarte (2009), "On the employment effects of productivity shocks: the role of inventories, demand elasticity and sticky prices", Journal of Monetary Economics, Volume 56, pp.328-343.

Citigroup-Oxford Martin School (2015), "Technology at Work: The Future of Innovation and Employment", http://www.oxfordmartin.ox.ac.uk/publications/view/1883.

Comin, D. A and M. Mestieri (2013) "Technology Diffusion: Measurement, Causes and Consequences" NBER Working Paper No. 19052.

Criscuolo, C., P.N. Gal, and C.Menon (2014), "The Dynamics of Employment Growth: New Evidence from 18 Countries", CEP Discussion Paper No 1274. http://cep.lse.ac.uk/pubs/download/dp1274.pdf

Davidson, P. (2012), "3-D printing could remake U.S. manufacturing". USA Today.

Davis, E. and G.Marcus (2015), "Commonsense Reasoning and Commonsense Knowledge in Artificial Intelligence", Communications of the ACM, September, Vol.58, No.9.

Davis, F.R. (2014), "Banned: A History of Pesticides and the Science of Toxicology". New Haven: Yale University Press.

De Backer, K. et al. (2016), "Reshoring: Myth or Reality?", OECD Science, Technology and Industry Policy Papers, No. 27, OECD Publishing, Paris.

Decker.R., J.Haltiwanger, R.S.Jarmin and J.Miranda (2014), " The Secular Decline in Business Dynamism in the U.S". http://econweb.umd.edu/~haltiwan/DHJM_6_2_2014.pdf

Delebecque, C. and J. Philp (2015), "Training for synthetic biology jobs in the new bioeconomy". Science, June 02, DOI: 10.1126/science.caredit.a1500143.

DSTI/ICCP/IIS(2014)6), "ICTs and Jobs: Complements or Substitutes – The Effects of ICT Investments on Labour Demand in 19 OECD Countries."

DSTI/IND/STP/ICCP(2016)1 – *The Next Production Revolution: An Interim Project Report*

DSTI/IND/STP/ICCP(2015)8/REV1 – *Enabling the Next Production Revolution*

Elliott, S.W. (2014), "Anticipating a Luddite Revival", *Issues in Science and Technology*, Spring, National Academy of Sciences, National Academy of Engineering, Institute of Medicine, University of Texas at Dallas.

E4tech (2014), "Biorefining in Scotland research project". Final Report, Version 2.0. E4tech (UK) Ltd, London.

European Commission, (2013), "Options for Strengthening Responsible Research and Innovation."

Evans, P. C. and M. Anninziata (2012), "Industrial Internet: Pushing the Boundaries of Minds and Machines", General Electrics, 26 November, www.ge.com/docs/chapters/Industrial_Internet.pdf.

Fraunhoffer (2015), "Analysis of the Impact of Robotic Systems on Employment in the European Union". https://ec.europa.eu/digital-single-market/news/fresh-look-use-robots-shows-positive-effect-automation

Frey, C.B and M.A.Osborne (2013), 'The Future of Employment: How Susceptible are Jobs to Computerisation?' Oxford Martin School Working Paper.

Gibson I., D. Rosen and B. Stucker (2015), "Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing", 2nd ed., Springer, New York.

Goos, M. and A.Manning, (2007), "Lousy and Lovely Jobs: The Rising Polarization of Work in Britain", Center for Economic Performance Discussion Papers DP0604, December.

Hoos, H.H. (2012), "Programming by optimization", Communications of the ACM, Volume 55, No.2, pp.70-80.

Jasanoff, S. (2003), "(No?) Accounting for Expertise." *Science and Public Policy* 30 (3): 157–62. doi:10.3152/147154303781780542.

Jasanoff, S. (2005), "Designs on Nature: Science and Democracy in Europe and the United States". Princeton, N.J: Princeton University Press.

Kamenova, K. and T. Caulfield. (2015), "Stem Cell Hype: Media Portrayal of Therapy Translation." *Science Translational Medicine* 7 (278): 278ps4–278ps4. doi:10.1126/scitranslmed.3010496.

Keasling, J. (2015), "Building an opportunity space for synthetic biology", International Innovation 185, 24-25.

Khatchadourian, R. (2015), "We Know How You Feel: Computers are learning to read emotion, and the business world can't wait", The New Yorker, January 19th edition. http://www.newyorker.com/magazine/2015/01/19/know-feel

Kirby, T. (2014), "Controversy Surrounds England's New NHS Database." *The Lancet* 383 (9918): 681. doi:10.1016/S0140-6736(14)60230-0.

Levy F. and R.J.Murnane (2013), "Dancing with Robots: Human Skills for Computerized Work". http://dusp.mit.edu/sites/dusp.mit.edu/files/attachments/publication/Dancing-With-Robots.pdf

Lorentz, M., M.Rüsmann, R.Strack, K.L.Lueth and M.Bolle (2015), "Man and Machine in Industry 4.0: How Will Technology Transform the industrial Workforce Through 2025?", The Boston Consulting Group. https://www.bcgperspectives.com/content/articles/technology-business-transformation-engineered-products-infrastructure-man-machine-industry-4/

Lux Research, 2015, "Synthetic biology: applications and lessons learned in the field of bio-based materials and chemicals". April 16, 2015, State of the Market Report. https://portal.luxresearchinc.com/research/report_excerpt/19239

Mandel, M. (2012), "Beyond goods and services: The (unmeasured) rise of the data-driven economy", Progressive Policy Institute, 10 April, www.progressivepolicy.org/2012/10/beyond-goods-and-services-the-unmeasured-rise-of-the-data-driven-economy/.

MarketsandMarkets (2014), "Additive Manufacturing & Material Market by Technology, by Material (Plastics, Metals, and Ceramics), by Application, and by Geography – Analysis & Forecast to 2014-2020", MarketsandMarkets, Dallas.

Markoff, J. (2015a), 'A Learning Advance in Artificial Intelligence Rivals Human Abilities', New York Times, December 10th. http://www.nytimes.com/2015/12/11/science/an-advance-in-artificial-intelligence-rivals-human-vision-abilities.html?_r=0

Markoff, J. (2015b), "Machines of Loving Grace: The Quest for Common Ground Between Humans and Robots", Harper Collins Publishers.

McGowan, A., M., D. Andrews, C. Criscuolo and G. Nicoletti (2015), "The Future of Productivity", OECD Publishing, Paris, http://dx.doi.org/10.1787/9789264248533-en.

MGI (2013), Disruptive Technologies: Advances that Will Transform Life, Business, and the Global Economy, McKinsey & Company, www.mckinsey.com/~/media/McKinsey/dotcom/Insights%20and%20pubs/MGI/Research/Technology%20and%20Innovation/Big%20Data/MGI_big_data_full_report.ashx.

Miller, B. and R.Atkinson (2013), "Are Robots Taking Our Jobs, or Making Them?", The Information Technology and Innovation Foundation". http://www2.itif.org/2013-are-robots-taking-jobs.pdf

Mokyr, J., C.Vickers and N.L Ziebarth (2015), "The History of Technological Anxiety and the Future of Economic Growth: Is This Time Different", Journal of Economic Perspectives, Volume 29, Number 3, pp 31-50.

Mokyr, J. (2014). Remarks at the *OECD-NBER Conference on Productivity and Innovation in the Long-Run*. http://www.oecd.org/industry/ind/proceedings-productivity-growth-and-innovation-in-the-long-run.pdf.

Nature (2013), "Sharing data in materials science", 28th November, Vol.503, pp.463-464.

Nesse, R. (2014), "The Fragility of Complex Systems", in Brockman, J. (ed), *What Should We Be Worried About?*, Harper Perrenial.

Nordhaus, W. (2007), "Two centuries of Productivity Growth in Computing", Journal of Economic History 67(1), pp.17-22.

OECD (2013a), "Interconnected Economies: Benefitting from Global Value Chains", OECD Publishing, Paris.

OECD (2013b), "Supporting Investment in Knowledge Capital, Growth and Innovation", OECD Publishing, Paris.

OECD (2015a), "Data-Driven Innovation: Big Data for Growth and Well-Being", OECD Publishing, Paris. DOI: http://dx.doi.org/10.1787/9789264229358-en.

OECD (2015b), "The Future of Productivity", OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264248533-en

OECD (2015c), "OECD Science, Technology and Industry Scoreboard 2015", OECD Publishing, Paris.

OECD (2016a forthcoming), "The convergence of industrial biotechnology with green chemistry: an issues paper", OECD Publishing, Paris.

OECD (2016b), "Nanomaterials in Waste Streams: Current Knowledge on Risks and Impacts", OECD Publishing, Paris.

Packer, J. (2008), "Mobility without Mayhem: Safety, Cars, and Citizenship". Durham: Duke University Press.

PEW Foundation (2014), “AI, Robotics and the Future of Jobs”, http://www.pewinternet.org/2014/08/06/future-of-jobs/

Philp, J.C. (2015), “Balancing the bioeconomy: supporting biofuels and bio-based materials in public policy”. *Energy & Environmental Science* 8, 3063-3068.

Pidgeon, N.F., R.E. Kasperson, and P. Slovic, eds. (2003), “The Social Amplification of Risk”, Cambridge: Cambridge University Press.

Pollack, M.A. and G.C. Shaffer (2009), “When Cooperation Fails: The International Law and Politics of Genetically Modified Foods”, OUP Oxford.

Pratt, G. (2015), “Is a Cambrian Explosion Coming for Robotics”, Journal of Economic Perspectives, Volume 29, number 3, Summer 2015, pp.51-60.

Reardon, S.(2015), “Gene-Editing Summit Supports Some Research in Human Embryos.” *Nature News*. Accessed December 22. doi:10.1038/nature.2015.18947.

Rigby, M. (2015), “Future-proofing UK manufacturing: Current investment trends and future opportunities in robotic automation”, Barclays. https://www.barclayscorporate.com/content/dam/corppublic/corporate/Documents/research/automation-report.pdf

Rotman, D. (2013), ‘How Technology is Destroying Jobs’, MIT Technology Review, June 12th.

Stewart, I, D.Debapratim and A.Cole (2014?), “Technology and People: The great job-creating machine”, Deloitte, http://www2.deloitte.com/uk/en/pages/finance/articles/technology-and-people.html

Summers, L.H. (2014), “On the Economic Challenge of the Future: Jobs”, July 7th, The Wall Street Journal. http://www.wsj.com/articles/lawrence-h-summers-on-the-economic-challenge-of-the-future-jobs-1404762501

Teresko, J. (2008), “Designing the Next Materials Revolution”, IndustryWeek.com, November 1st, http://www.industryweek.com/none/designing-next-materials-revolution

The Economist (2015), “New Materials for Manufacturing”, Technology Quarterly, 8th December, http://www.economist.com/technology-quarterly/2015-12-05/new-materials-for-manufacturing

Vodafone (2015), “M2M Barometer 2015 report”, Vodafone, http://m2m-mktg.vodafone.com/barometer2015.

Watson, R.R. and V.R. Preedy (2016), “Genetically Modified Organisms in Food: Production, Safety, Regulation and Public Health”, Amsterdam: Elsevier Science. http://uclibs.org/PID/277991.

Weilerstein, P. (2014). NCIIA: students as the vanguard in a geographically dispersed approach to stimulating science and technology innovation. In Engel, J. (Ed.) Global Clusters of Innovation: Entrepreneurial Engines of Economic Growth around the World (pp., 359-377). Cheltenham, Edward Elgar

Winner, L. (1986), “The Whale and the Reactor: A Search for Limits in an Age of High Technology”, Chicago: University of Chicago Press.

OECD WEEK 2016

www.oecd.org

OECD Paris
2, rue André-Pascal, 75775 Paris Cedex 16
Tel.: +33 (0) 1 45 24 82 00