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ENABLING THE NEXT PRODUCTION REVOLUTION: A SUMMARY OF MAIN MESSAGES AND POLICY LESSONS

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Enabling the Next Production Revolution: A Summary of Main Messages and Policy Lessons

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Introduction and 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 (IoT), advanced robotics) to new materials (e.g. bio- or nano-based) to new processes (e.g. data driven production, artificial intelligence, synthetic biology). This report sketches the medium-term economic and policy implications of these technologies. As these technologies transform production, they will have far-reaching consequences for productivity, employment, skills, income distribution, trade, well-being and the environment. The more that governments understand how production could develop, the better placed they will be to help achieve the benefits and address the challenges.

2. This paper summarises the findings of the OECD cross-cutting project "Enabling the Next Production Revolution", implemented over the 2015-2016 biennium. The Directorate for Science, Technology and Innovation (STI) has led this work, with inputs also provided by the Environment Directorate (ENV) and the Secretary-General's office (SGE). A project interim report, C/MIN(2016)5 – *Enabling the Next Production Revolution: The Future of Manufacturing and Services*, was submitted to the Ministerial Council Meeting on 1-2 June 2016.

Key messages

3. New production technologies will play important roles in determining the availability and nature of work. Part of a strategy for coping with rising shares of high and low-wage jobs must involve the creation and retention of technology-intensive production work. Jobs in manufacturing are often well-paid (on average, in the United States, manufacturing workers are paid at least 20% more than workers in services and non-manufacturing (Helper, Kruger and Wial, 2012)). And manufacturing output generates more and broader economic activity in the rest of the economy than any other sector. Technological development will inevitably disrupt today's industries, and incumbent firms will be challenged as new technologies redefine the terms of competitive success. The precise pace and scale of inevitable future adjustments are unknown. But resilience and prosperity will be more likely in countries with **more forward-looking policies, better functioning institutions, better educated and informed citizens, and critical technological capabilities in a number of sectors.**

4. Command over these technologies also promises greener production, safer jobs (with some hazardous work performed by robots), new and more customised goods and services, and productivity growth. Indeed, **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.

5. While new technologies will create jobs through many channels, and productivity-raising technologies will benefit firms and the economy overall, the associated adjustments could be significant and take time. Hardship could affect many if labour displacement were to occur in a major sector, or in many sectors simultaneously. Policymakers need to monitor and actively manage the adjustments, for instance through forward-looking policies on skills, labour mobility, social protection systems and regional development. The Horizontal Project on 'Going Digital' will examine this issue in depth.

6. Compared to earlier industrial revolutions, induced by steam and electrification, the creation and international spread of inventions that can transform production will occur quickly. 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 timelines for the delivery of important production technologies.

7. **Diffusion of the technologies must include not only the hardware**, but also the complementary intangible investments and know-how needed to fully exploit the technologies, ranging from skills to new forms of business organisation. Here, among other things, the efficient deployment and reallocation of human and financial resources is essential. 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 can help.** Especially among SMEs, a major challenge will be the digital transformation of firms which were not born digital. Many entrepreneurs do not fully understand the uses and implications of technologies such as the IoT. Institutions with specific remits to aid diffusion, such as technical extension services (which provide information and outreach, especially for SMEs), tend to receive low priority in innovation policy overall. But such institutions can be effective if properly designed, incentivised and resourced.

9. **From digitally integrated supply chains to computer simulation of the properties of new materials, data will be central to many aspects of 21st century production.** Policy should encourage investments in data that have positive spillovers within and across industries. Obstacles to the reuse and sharing of data, including public data, should be examined, and data governance frameworks developed that address privacy and digital security considerations. The quality of digital infrastructure, including access to high-powered computing, will be critical for firms in many sectors.

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 industry and education and training institutions is often required, and this need may grow as the knowledge content of production rises. Effective systems for life-long learning and workplace training are essential, such that skills upgrading matches the pace of technological change and retraining can be accessed when needed. Digital skills, and skills which complement machines, are vital. Also important is to ensure good generic skills – such as literacy, numeracy and problem-solving – throughout the population, in part because generic skills are the basis for learning fast-changing specific skills. These and other skills-related issues are being assessed at country level as part of the OECD’s ongoing Skills Strategy.

11. **Sound science and R&D policies are important.** The technologies addressed in this report have arisen because of advances in scientific knowledge and instrumentation emanating from both the public and private sectors. Many of the research challenges critical to the next production revolution are multidisciplinary. Evaluation metrics for research programmes should properly incentivise multidisciplinary research, research scale-up (such as through test-bed demonstration) and linkages across stakeholders.

12. **Public understanding and acceptance** of new production technologies also matter. A close connection exists between public resistance to new technologies and the disruption of trust in scientific and regulatory authorities. Policymakers and institutions should voice realistic expectations about technologies, duly acknowledging uncertainties. Science advice should be demonstrated to be unbiased and trustworthy. Public deliberation can also help to build understanding between scientific communities and the public.

13. Foresight, if applied appropriately, could support policy making during times of technological and socio-economic change. Using participatory methods, key actors and stakeholders can be mobilised to form shared views about the future, negotiate their future stakes and interests, and agree on joint and

coherent actions. **Foresight processes can bring benefits in themselves, such as strengthened stakeholder networks.** They can also help direct policies for science and R&D, encourage co-ordination across policy domains, and trigger organisational innovations.

14. **Long-term thinking is essential.** In addition to addressing short-term challenges, leaders in business, education, unions and government must be ready to frame policies and prepare for developments beyond typical election cycles. Reflection is also required on **how policy priorities might need to evolve**, driven for instance by technological change itself. For example, **major challenges to the intellectual property system** could soon arise from the emerging ability of machines to create (at least one machine-derived invention has already been patented).

15. In conclusion, the NPR poses multiple complex policy challenges. But through judicious policy, the opportunity exists to positively influence the next production revolution now.

Next steps

16. The full report from this project will be available as: OECD (forthcoming - 2017), *The Next Production Revolution: Implications for Governments and Business*. Among other uses, the findings from this work will directly inform production-related aspects of the OECD's horizontal project on digital transformation - "Going Digital - Making the Transformation Work for Growth and Well-being". The publication and its findings will also be used to support ongoing exchanges on the subject of future production with OECD Members and Partners.

1. Productivity and the technologies of the next production revolution

17. Raising rates of economic growth is a priority for most OECD governments today. Over the longer-term, shrinking working-age populations, combined with environmental constraints, mean that growth in many economies will increasingly depend on productivity-raising innovation. Emerging production technologies will affect productivity through many routes. For instance:

- The combination of new sensors and control devices, data analytics, cloud computing and the Internet of Things (IoT) is enabling increasingly intelligent and autonomous machines and systems. Intelligent systems can almost entirely eliminate errors in some production processes (because sensors allow every item to be monitored). Machine downtime and repair costs can be greatly reduced when intelligent systems predict maintenance needs. Savings can be realized when industrial processes are simulated before being built. Data-driven supply chains speed the time to deliver orders. And production can be set to meet actual rather than projected demand, reducing the need to hold costly inventories.

- By being faster, stronger, more precise and consistent than workers, robots have vastly raised productivity on assembly lines, particularly in the automotive industry. They will do so again in an expanding range of sectors and processes, as industrial robotics advances.

- Progress in materials science and computation will permit a simulation-driven approach to developing new materials, reducing 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 separately spray painting plastics, reducing costs by USD 100 per vehicle.

But there is much unexploited potential for productivity growth…

18. The technologies considered in the OECD's work have more to contribute to productivity than they currently do. Often, their use is predominantly in larger firms. 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. Even in larger firms, many technologies are underused. Unexploited opportunities exist throughout industry.

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

19. 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. And the mere availability of a technology is not sufficient for its uptake and successful use. Realising the benefits of a technology often requires that it be bundled with investments in complementary assets such as new skills and organisational forms and that better adapted business models are invented.

1.1. Work, automation and the new technologies of production

20. 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). And 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 some workers.

Progress in computing is leading to novel machine capabilities and automating tasks easily represented in computer code

21. The routine tasks of most operatives in manufacturing are now automated in most OECD countries. Many labour-saving innovations are underway. For instance, 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.

22. In recent decades, the share of employment in high- and low-wage jobs has increased in OECD countries' labour markets, while the share of employment in middle-wage jobs has fallen. This polarisation has been linked to the falling share of employment in occupations that entail many routine tasks (i.e. tasks easily described by computer code) (Goos and Manning, 2007).

Box 1. How large are the productivity effects?

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

- In the United States, output and productivity in firms that adopt data-driven decision making are 5% to 6% higher than expected given those firms' other investments in 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 – is associated with a 14% increase in labour productivity on average, but with significant cross-industry variations (Barua et al., 2013).
- The IoT 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).
- Warehouses equipped with robots made by Kiva Systems can handle four times as many orders as un-automated warehouses (Rotman, 2013).

But new technologies also create jobs through a number of channels

23. A technology-driven increase in productivity benefits the economy through one or more of the following channels: lower prices of output, higher workers' wages, or higher profits. Lower output prices raise the real incomes of consumers. This can increase demand for other goods or services. And higher workers' wages may raise demand and job creation in other markets. Higher profits are distributed to shareholders, who may spend all or part of this new income, adding to aggregate demand. And increases in savings, among shareholders and workers, eventually lowers interest rates and raises investment, creating jobs. Key issues concern: the quantitative balance between jobs lost and jobs gained; the characteristics of the jobs lost and the characteristics of those created; and, the duration and efficiency of the labour market and other economic adjustment processes involved. These adjustment processes are conditioned by the efficiency of institutions (such as financial services, that mediate between savings and investment), and a range of micro- and macro-economic policies.

Productivity-raising technologies benefit the economy

24. Historical evidence is overwhelmingly positive regarding the long-term economic and labour market effects of technological change. To cite just a few country-level studies: Investments in ICT are estimated to have raised total labour demand in 19 OECD countries over the period 1990-2007 (but to have reduced it after 2007). ICT investments appear to have no effects on total labour demand in the long run. A permanent decrease in the cost of ICT capital reduces labour demand per unit of output, but increases output by the same proportion (OECD, 2016a). And from 1964 to 2013, against a background of accelerating automation, the United States economy created 74 million jobs (Levy and Murnane, 2013).

25. Evidence at the level of firms and industries mostly shows that productivity-enhancing technology – which is often also associated with new business models - 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.

But adjustment might be painful and policymakers need to monitor and prepare for adjustment processes

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

27. Almost certainly, as automation advances, a larger share of the future workforce will need to perform many non-routine tasks. But the specific types of work brought by new technology is 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.

Policymakers need to monitor and prepare for possible adjustment processes

28. The precise pace and scale of inevitable future adjustments are unknown. In the worst case, 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, so that people can adapt and thrive in the NPR.

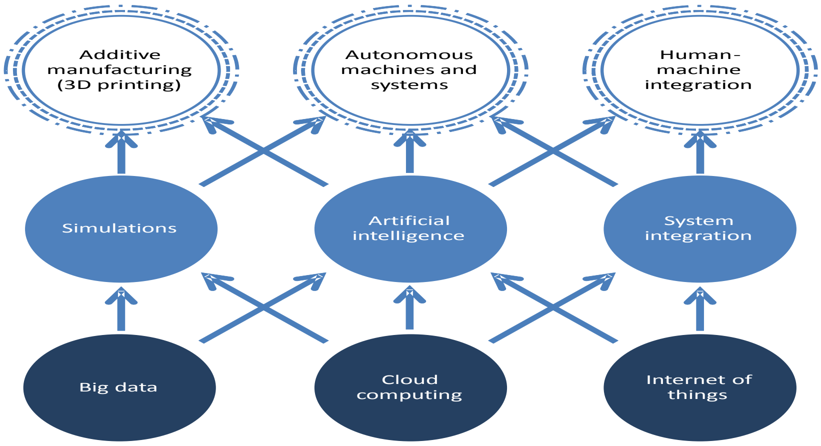
2. Digital technologies and future production

29. Two trends make digital technologies transformational for production: (i) their falling cost, which has allowed wider diffusion; and, (ii) the combination of different ICTs, and their convergence with other technologies (thanks in particular to embedded software and the IoT). In a stylised way, Figure 1 depicts key ICTs enabling the digital transformation of industrial processes. The technologies at the bottom of Figure 1 enable those on top, as indicated by the arrows.

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

30. 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).

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



Cloud computing enhances agility, scalability and interoperability

31. 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 computationally intensive and require supercomputers. Especially for start-ups and SMEs, cloud computing has increased the availability, capacity and affordability of computing resources.

The Internet of Things (IoT) will bring radical change

32. The term IoT refers to the connection of devices and objects to the Internet. The IoT can bring improved process efficiencies, customer service, speed of decision-making, consistency of delivery and transparency/predictability of costs. To give an example of potential impact, it has been estimated that 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).

Barriers to ICT diffusion, interoperability and standards should be lowered

33. Many businesses, and in particular SMEs, lag in adopting ICTs. For instance, the adoption of supply chain management, enterprise resource planning (ERP), and cloud computing applications by firms is still much below that of broadband networks or websites. But it is these advanced ICTs that enable digitalised industrial production. An important aspect of interoperability for the IoT is identification and numbering policies.

Box 2. Promoting skills and investments in and use of ICT and data

National and Federal/sub-national education systems, in collaboration with business and trade unions, need to support the development of ICT-related skills, starting with basic ICT skills, and including specialist data skills. The educational needs extend beyond ICT to include science, technology, engineering and mathematics (STEM). This calls for measures to: (i) promote digital literacy in schools; (ii) further develop vocational and on-the-job training; and, (iii) better connect areas of education, for instance through strategic alliances between universities and businesses.

Technical skills are not enough. Technical skills need to be complemented with know-how in domain-specific issues (including knowledge of production processes) as well as "soft skills" such as communication, self-direction, creative thinking and problem solving. Especially for low-skill groups, acquiring these skills is particularly important in coping with disruption to existing industries.

Governments aiming to promote the supply of key ICTs should consider supporting investments in R&D on enabling technologies such as big data analytics, cloud and high-performance computing, and the IoT, as well as in security- and privacy-enhancing technologies.

Governments should consider using demand-side policies to encourage investments in and adoption of key enabling ICTs, especially by SMEs. This can be done through activities such as awareness raising, training, mentoring and voucher schemes.

Governments should encourage investments in data that have positive spillovers across industries and higher social than private value, while addressing the low appropriation of returns to data sharing.

Governments should promote open standards, including in application programming interfaces (APIs) and data formats. Standards based on technologically open reference models could boost data interoperability and reuse, and digital services, and reduce technological lock-ins, while enhancing competition.

Liability, transparency, and ownership

34. 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).

35. 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 (see Box 3).

Box 3. Addressing emerging risks and uncertainties

Governments may need to act if regulatory uncertainties prevent the adoption of ICTs. This is especially the case if regulations designed for the pre-digital era inadvertently shield incumbents from new forms of competition.

Governments should support a culture of digital risk management (as promoted by the *2015 OECD Recommendation on Digital Security Risk Management for Economic and Social Prosperity*). Traditional security approaches might not fully protect assets in a digital environment, and are likely to stifle innovation (OECD, 2016b).

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

Obstacles to the reuse, sharing and linkage of data can take many forms and should be examined. Technical barriers can include constraints such as difficult machine readability of data across platforms. Legal barriers can also prevent data reuse and sharing. For example, the "data hostage clauses" found in many terms-of-service agreements can sometimes prevent customers from moving to other providers.

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

Governments may seek to promote the responsible use of personal data to prevent privacy violations. Governments could promote privacy-enhancing technologies and empower individuals through greater transparency of data processing, and greater data portability. Governments may need to increase the effectiveness (i.e. resourcing and technical expertise) of privacy enforcement authorities.

Governments and competition policy authorities may need to assess market concentration and competition barriers using up-to-date definitions of the relevant markets and consideration of the potential consumer detriments of privacy violations. This may also require dialogue between regulatory authorities (addressing competition, privacy and consumer protection). Germany's Act against Restraints on Competition (ARC) was recently amended, with adjustments made to provisions regarding market definition, in order to better suit the digital economy.

Further thinking is needed on the attribution of responsibility and liability for inappropriate data-driven decisions. Governments may have to assess whether existing regulations and legislation fully address the challenge of attributing responsibility and liability for damaging data-based decisions (as between decision makers and providers of data and data analytics). Multi stakeholder dialogue at national and international level may help by exchanging best practices. **Careful examination is needed of the appropriateness of fully automated decision making, transparency requirements and required human intervention in areas where the potential harm of automated decisions could be significant.** More studies are needed to determine how best to assess the appropriateness of algorithms without violating existing IPRs on such algorithms.

3. Nanotechnology – an enabler to the next production revolution

36. 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.

Box 4. Nanotechnology - main policy considerations

Nanotechnology requires increased efforts in institutional and possibly international collaboration. The entirety of research and engineering tools required to set up an all-encompassing R&D infrastructure for nanotechnology might be prohibitively expensive. State-of-the-art equipment costs several million euros and often requires the construction of bespoke buildings. Moreover, some of the most powerful research instruments exist as prototypes only. It is therefore almost impossible to gather an all-encompassing nanotechnology infrastructure within a single institute or even region.

Support is needed for innovation and commercialisation in small companies. The relatively high cost of nanotechnology R&D hampers the involvement and success of small companies in nanotechnology innovation. Large companies are better placed to assimilate nanotechnology due to their critical mass in R&D and production, their ability to acquire and operate expensive instrumentation, and their ability to access and use external knowledge. Policy makers could seek to improve SMEs' access to equipment by: (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 must be addressed in internationally collaborative approaches. Regulatory uncertainties regarding risk-assessment and approval of nanotechnology-enabled products severely hamper the commercialisation of nano-technological innovation. This is because products awaiting market entry are sometimes shelved for years before a regulatory decision is made. Policies should also support the development of transparent and timely guidelines for assessing the risk of nanotechnology-enabled products, while also striving for international harmonisation in such guideline.

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

4. Bio-production and industrial biotechnology

37. Bio-based manufacturing - the most potent symbol of which is the integrated bio-refinery – holds the promise of producing 'green' energy, chemicals and materials. The overarching policy issue relates to the sustainability of biomass supply. Linked to this is the need to de-risk investments in new, and sometimes technologically unproven, demonstrator facilities and biorefineries.

38. Several decades of research in biology have now also yielded synthetic biology – which aims to design and engineer biologically-based parts, novel devices and systems - 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, artificial photosynthesis and micro-organisms that produce biofuels are just some among recent breakthroughs.

Box 5 Bio-production and industrial biotechnology - main policy considerations

Overarching bioeconomy strategies could help governments develop coherent mixes of policies to facilitate the transition to a more bio-based economy. The variety of stakeholders, range of policy instruments and scope of potential impacts are great. A well-crafted bioeconomy strategy could create synergies among policies and enhance overall impact.

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

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

A main challenge in bio-based production is its multi-disciplinarity. Research and training will have to create not only the technologies required, but also the technical specialists. There are ways for governments to tackle this challenge, such as by organising research degrees with a focus on business, not academic, outcomes.

Governments should focus on three objectives as regards regulations: 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 more flexible, enabling the use of agricultural and forestry residues and domestic wastes in bio-refineries.

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

5. 3D printing, production and the environment

39. 3D printing is expanding rapidly owing to falling printer and materials prices, the rising quality of completed objects, and innovation. 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 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.

40. 3D printing can enable more sustainable material use because it: permits many materials to be shaped in ways previously possible only with plastics; lowers barriers to switching between materials by reducing economies of scale in some processes; and, can allow fewer chemical ingredients to yield more variation in material properties by varying printing processes. 3D-printed parts can also lower the environmental impacts of some products by: (i) printing replacement parts for legacy products that would otherwise be discarded; and (ii) reducing a product's weight or otherwise improving its energy efficiency.

Box 6. 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). Printers can also minimise material impacts by using compostable biomaterials. Printer design and operation can also reduce waste by using less support material (printers often use support materials in addition to modelling material). 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;
- Taking into account the interests of all stakeholders, examining how best to remove intellectual property barriers to enable 3D printing of repair parts for legacy products that lack existing supply chains. For example, a broken washing machine may only require a single part 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

41. Advances in scientific instrumentation, such as atomic-force microscopes, have allowed scientists to study materials in more detail than ever before. Developments in computational simulation tools for materials have also been critical. Today, materials are emerging with entirely novel properties, 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).

42. The era of trial and error in materials development is ending. Modelling and simulation of the structure and properties of materials can now inform decisions on how the material might be used in products. Shortly, engineers will design both the product and its constituent materials (Teresko, 2008). A simulation-driven approach to materials development will reduce time and cost as companies perform less repetitive analysis, and the time between materials discovery and their commercial use will be shortened. Simulation will also permit better products, such as stronger complex structures.

Box 7. New materials and the next production revolution - main policy considerations

Policy can shape the development of the materials innovation ecosystem, broaden the potential pool of collaborators, and promote more efficient investment strategies. No single company or organisation will be able to own all the technologies in an e-collaborative materials innovation ecosystem. A public-private investment model is warranted, particularly with regard to building cyber-physical infrastructure and developing the future workforce.

New materials will raise new policy issues and give new emphases to long-standing policy concerns. For instance, new cybersecurity risks could arise because, in a medium-term future, a 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 experimental data in return for access to modelling tools, for example (Nature, 2013)). Advances in materials also require close collaboration between industry, universities, research funding agencies and government laboratories.

Interdisciplinary research and education are needed. Materials research is inherently interdisciplinary, with contributions come from engineering and materials science, physics, chemistry, chemical engineering, bio-engineering, applied mathematics, computer science, and mechanical engineering, among other fields.

There is also need for policy co-ordination across the materials innovation infrastructure at national and international levels. Major efforts are underway to develop materials information infrastructure and associated data standards in professional societies. A need for international policy co-ordination arises from the necessity of federating elements of the cyber-physical infrastructure across a range of European, North American and Asian investments and capabilities, as it is too costly (and unnecessary) to replicate resources that can be accessed via web services with user support. Ultimately, good policies are required because of the need to change the culture of sharing data and, in particular, to facilitate a pre-competitive culture of e-collaboration.

Deliberation between research bodies, firms, government research laboratories, standards organisations, and professional societies working to develop new and improved materials have predominantly been concerned with the compatibility of data formats. But this needs to evolve towards a focus on how to use these data to support decisions in materials discovery and development. Access to high performance computing and cloud storage is important, to which pre-competitive public-private consortia and government policy can contribute.

7. Public acceptance and new technologies

43. 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). 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).

44. Various NPR technologies have raised public concerns of different kinds. Some concerns have to do with risk, such as how nano-technologies might affect human health (recent work has found significant knowledge gaps with respect to the final disposal of nanoparticles (OECD, 2016c)). 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 8. 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). Multistakeholder approaches can help achieve realistic assessments of a technology's potential.

Science advice must be trustworthy. There is a close connection between public resistance to novel technologies and the disruption of trust in public scientific and regulatory authorities. 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 fully accountable.

Ethical and social issues should be included in major research endeavours. The planners of the Human Genome Project (HGP) recognised that 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. The next generation of these approaches integrates social considerations not at the end of technology pipelines, but in the course of their development.

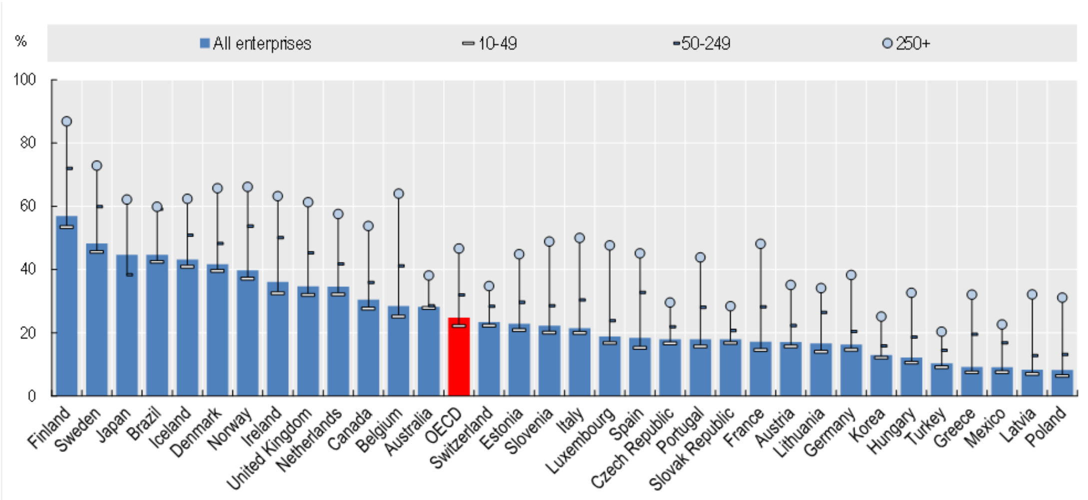
Public deliberation is important for mutual understanding between scientific communities and the public, and should inform innovation policy. Deliberation can take various forms, from inclusion in national advisory processes and public enquiries, to citizen panels and town hall meetings (pioneered in Denmark and elsewhere for a broad range of emerging technologies relevant to the NPR).

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

45. A critical issue is how already-developed technologies diffuse. The issue is twofold. First, it is about increasing new-firm entry and the growth of firms which are major carriers of new technology. Secondly, it is about increasing productivity in established firms which face obstacles to implementing technology. In the second case, small firms, in particular, tend to use key technologies less frequently than larger firms. In Europe, for instance, 36% of surveyed companies with 50 to 249 employees use industrial robots, compared to 74% of companies with 1 000 or more employees (Fraunhofer, 2015). And even though cloud computing has increased the availability and affordability of computing resources, smaller firms in almost all countries are less likely to use this technology than larger firms (Figure 2). The two aspects of technology diffusion - firm entry and growth, and more general adoption - involve different policy instruments.

Figure 2. Enterprises using cloud computing services by employment size class, 2016

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, ICT Database; Eurostat, Information Society Statistics Database and national sources, January 2017.

46. Several factors shape the diffusion process at national and international levels, including: (i) global connections via trade, FDI, and the international mobility of skilled labour; (ii) connections and knowledge exchange within national economies, such as the interaction between scientific institutions and businesses; (iii) the development of standards; (iv) the scope that exists for experimentation by firms – especially entrants – with new technologies and business models; and, (v) the extent of complementary intangible investments in R&D, skills, organisational know-how (i.e. managerial capabilities) and other forms of knowledge-based capital (OECD, 2015a). 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.

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

47. Institutions for technology diffusion are intermediaries, structures and routines that facilitate the adoption and use of knowledge, methods and technical means. Table 1 offers a typology. Some of the institutions involved, such as technical extension services, tend to receive low priority in the standard set of innovation support measures. But they can be effective, if well designed and properly resourced.

48. New diffusion initiatives are emerging, some of which are still experimental. Alongside established applied technology centres, such as Germany's Fraunhofer Institutes, there is an increase in partnership-based approaches. An example is the US National Network for Manufacturing Innovation (NNMI). The NNMI uses private non-profit organisations as the hub of a network of companies and universities to develop standards and prototypes in areas such as digital manufacturing and design.

Table 1. Initial typology of institutions for technology diffusion

Type	Operational mode (primary)	Example
Dedicated field services	Diagnostics, guidance and mentoring	Manufacturing Extension Partnerships (US); Mittelstand 4.0 competence centers (Germany); Labs Network Industrie 4.0 (Germany).
Technology-oriented business services	Advice linked with finance Capacity development	Industrial Research Assistance Program (Canada); I-Corps (US)
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 (UK)
Demand-based behavioural change	Knowledge transfer incentives	Innovation vouchers (multiple countries)
Technology partnerships	Collaborative applied research Prototyping and standards	National Network for Manufacturing Innovation (US)
Open source sharing	Open source sharing Virtual networks	Registry of Standard Biological Parts (US)

Box 9. The diffusion of new production technologies - main policy considerations

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

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

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

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

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

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

49. 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.

50. Foresight is a type of prospective analysis aimed at thinking about the future and shaping it. 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.

Foresight processes can bring many benefits

51. 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 futures is a pre-condition for devising policies to cope with unexpected developments. Furthermore, in a complex world, many phenomena must be seen from a number of viewpoints. Foresight involving participatory methods can incorporate necessarily diverse perspectives.

52. Most foresight activities also seek a common understanding of what a desirable future might be. Such *visions* and – associated to them – operational *roadmaps*, can be instruments for assembling key players around a *shared agenda*. By involving participants from different policy domains, policy co-ordination can also be fostered horizontally (i.e. across policy domains, or between parliament and government) and vertically (i.e. between ministries and executive agencies).

53. Government bodies also tend to be organised by rigidly demarcated policy domain. 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. Foresight processes have the potential to enlarge and renew the framing of policy issues.

Governments can create conditions which aid effective foresight

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

10. Cross-cutting policy considerations

Sound science and R&D policies are essential

55. 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 scale of public support for basic research; the procedures for allocating funds for public 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.

Many of the key research challenges are multidisciplinary and systemic in nature

56. Identifying priorities for government-funded manufacturing research programmes and initiatives is increasingly challenging due to the convergence of technologies and the complexity of modern manufacturing. To assess the impact of R&D investments – and decide where policy should focus – account must be taken of the increasingly blurred boundaries among manufacturing research domains. Many research challenges will need to draw on traditionally separate areas of manufacturing-related research (such as advanced materials, production tools, ICT, operations management). Many government-funded research institutions and programmes have also been constrained to only carrying out research, without the freedom to adopt additional relevant innovation activities or connect to other innovation actors. As a result, many government-funded research institutions and programmes are unable to bring together the right combination of capabilities, partners and facilities to address scale-up and convergence challenges.

57. Better evaluation of institutions and programmes may need new indicators, beyond traditional metrics such as numbers of publications and patents, including in areas such as: successful pilot line and test-bed demonstration, development of skilled technicians and engineers, repeat consortia membership, SME participation in new supply chains, and contribution to the attraction of FDI. Policy makers should avoid performance metrics that do not account for the systemic nature of the next production revolution.

Governments must create an environment which fosters business dynamism

58. 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 range of countries since the early 2000s. Governments must attend to a number of conditions which affect this dynamism, such as the availability of finance, timely bankruptcy procedures and strong contract enforcement (Calvino, Criscuolo and Menon (2016)).

Technological change is raising new challenges for the intellectual property (IP) system

59. One among a number of challenges to the IP system comes 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. For instance, among a number of issues, the patents system may need to be revised in a world where machines possess the capability to invent (as has effectively occurred already in the pharmaceuticals industry).

Distribution rather than scarcity will be a primary concern

60. 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

61. Rapid technological change challenges the adequacy of skills and training systems. Effective systems for life-long learning and firm-level training are essential, such that skills upgrading can match the pace of technological change and retraining can be accessed when needed. Digital skills, and skills which complement machines, are vital. Also important is to ensure good generic skills – such as literacy, numeracy and problem-solving – throughout the population, in part because generic skills provide a basis for learning fast-changing specific skills.

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

62. Many of the technologies examined in this report require more interdisciplinary education and research. 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 may be needed as the knowledge content of production rises

63. 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. Many other policy issues that affect skills systems today will continue to be important, such as establishing incentives for institutions to provide high-quality teaching. But it is not evident that emerging production technologies would *raise* their importance.

NPR may bring changes to labour market policies too

64. 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. For instance, resources for life-long learning and support for workers' transitions in mid-career may need to be enhanced.

Policymakers need to engage in long-term thinking

65. More public discussion is needed of the policy implications of new production technologies. As well as addressing today's needs, leaders in business, education, unions 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 Industrie 4.0 ("Plattform Industrie 4.0").

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

66. 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).

The next production revolution is likely to affect global value chains, but exactly how is uncertain

67. 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 GVCs has drawn attention to the economic consequences of operating in different parts of a GVC (OECD, 2013). GVCs are constantly evolving. 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*., 2016). However, evidence suggests that European companies which intensively use robots are less likely to locate production abroad. And features of some technologies, such as 3D printing, could lead to some production being brought closer to developed-country markets. Developments in China are also likely to play a role. China already 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 affect the use of production technologies in those markets.

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