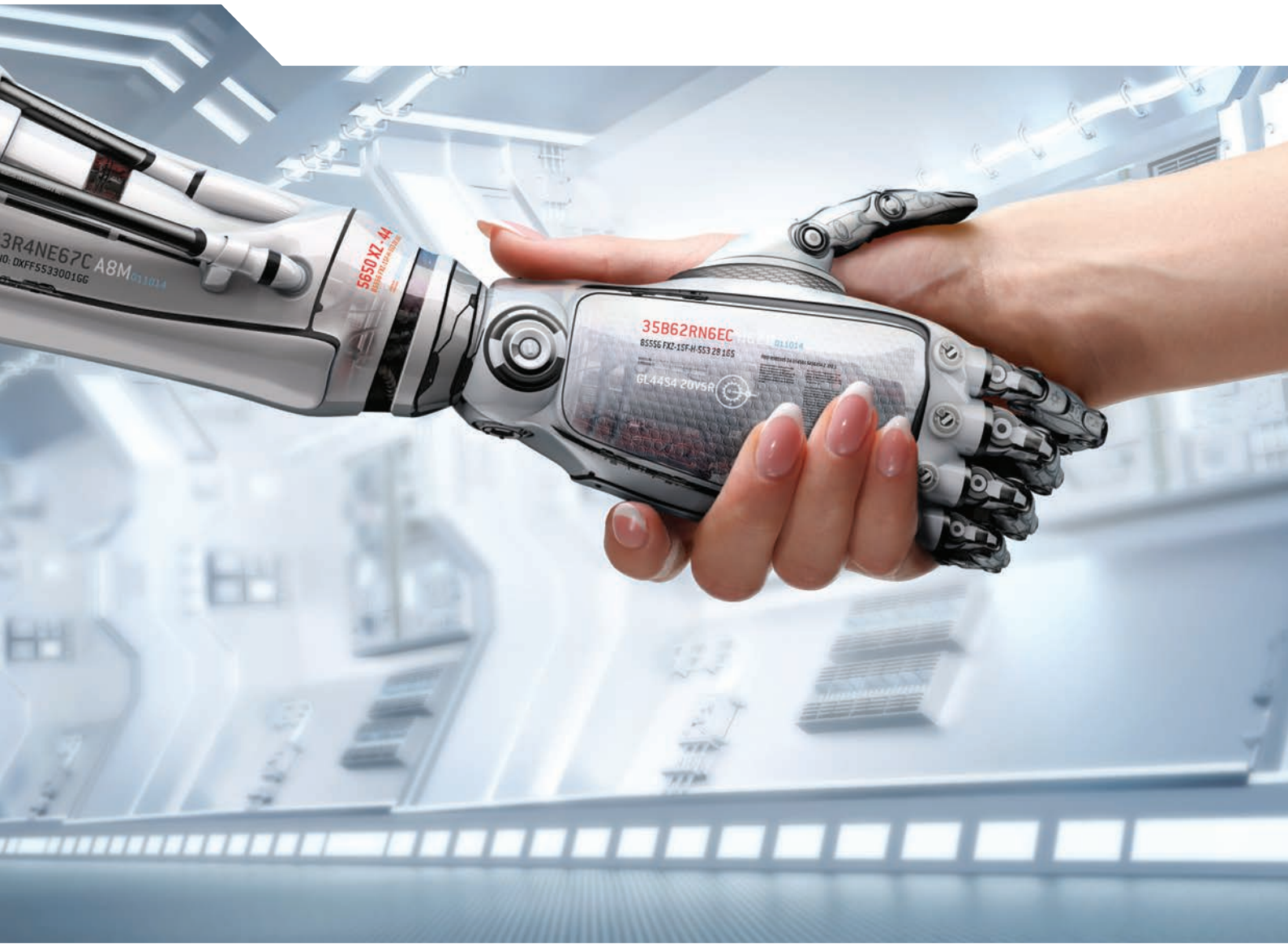
The Next Production Revolution

IMPLICATIONS FOR GOVERNMENTS AND BUSINESS



OECD

The Next Production Revolution

IMPLICATIONS FOR GOVERNMENTS AND BUSINESS



BETTER POLICIES FOR BETTER LIVES

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Preface

On an almost daily basis, we hear of technological breakthroughs ranging from artificial intelligence and 3D printing, to self-driving vehicles. We are entering a world of "digital manufacturing" and "the fourth industrial revolution". It is a pleasure, therefore, to present *The Next Production Revolution: Implications for Governments and Business*, an in-depth OECD assessment of the medium-term economic and policy implications of new and emerging production technologies.

How production might evolve has far-reaching consequences for productivity, employment, skills, income distribution, trade, well-being and the environment. And the policy implications of the next production revolution are far-reaching. Indeed, it is difficult to mention a major area of policy that will be unaffected. From research and education, to data security and infrastructure, the future of production is central to many aspects of the OECD's work.

New production technologies are reshaping the availability and nature of work. It is therefore important that strategies for inclusion understand this process. In fact, new production technologies tie together the critically important themes of productivity and inclusiveness, one of the key concerns of the OECD. As challenges related to population ageing multiply, OECD countries will need the productivity gains that these technologies can deliver. Most importantly, workers also need to be equipped to use these technologies, and policies need to be designed so that economies and societies cope well with the adjustments that these technologies entail.

From this year onwards, the OECD is increasingly focusing upon the digital transformation of the economy and society. This report illustrates just how pervasive and important digital technology is to production and how much more impact digital technology could have if its diffusion was more widespread. This is true even in fields that we do not usually think of as digital, such as industrial biotechnology and new materials.

New production technologies will also affect how we deal with climate change and the natural environment. Positive environmental effects could take many exciting forms, from industrial printing of products using bio-friendly materials, to writing genetic code that allows micro-organisms to make fuels, to drastically reducing waste in zero-defect factories.

The next production revolution is also relevant to the issue of trust in government. Public resistance to new technologies is linked to diminished trust in scientific and regulatory authorities. When the economic or social implications of certain new technologies are disruptive, such trust is particularly important. In this regard, this report offers a sober reflection on some of the hyperbole associated with new production technologies.

A further highlight of this report is the extensive assessment of developments in China. The OECD has worked closely with China on the subject of the next production

revolution during China's G20 Presidency. While China has many challenges to overcome, its achievements will have global ramifications.

Lastly, in keeping with the OECD's work on New Approaches to Economic Challenges (NAEC), multidisciplinarity remains essential in grasping today's real-world complexities. This report, therefore, lays out the emerging features of production across many technologies, from multiple policy standpoints and using different types of evidence and analysis. The more governments understand about how production is developing, the better positioned they will be to tackle emerging challenges and achieve economic, social and environmental goals.



Angel Gurría

Secretary-General of the OECD

Foreword

At the start of 2015 the OECD began work on a two-year project entitled Enabling the Next Production Revolution. The work set out to better understand the economic and policy implications of a set of technologies that are likely to significantly affect production over the medium term.

This work commenced with financial support from the Secretary-General's Central Priority Fund. The project greatly benefitted from voluntary contributions from the governments of Australia and the United Kingdom. Particular thanks are due to the government of Norway, whose support helped to widen the project's scope. Thanks are likewise due to the government of Sweden, particularly the Ministry for Enterprise and Innovation and the national innovation agency, Vinnova, for co-organising and hosting a major conference on the themes in this report, titled Smart Industry: Enabling the Next Production Revolution. The conference, held in Stockholm in November 2016, helped to discuss and refine analyses and policy ideas with policymakers, practitioners and academics. The conference was filmed, and the proceedings can be viewed at www.vinnova.se/en/misc/Smart_Industry_Conference/.

Owing to the cross-cutting character of the work on the next production revolution, the chapters of this publication were discussed and declassified by various OECD Committees, including the Committee for Scientific and Technological Policy (which had oversight responsibility for the project); the Committee for Industry, Innovation and Entrepreneurship, the Committee for Digital Economy Policy and the Environment Policy Committee. The comments and inputs formulated by delegates to these OECD official bodies are gratefully acknowledged. Within the OECD Secretariat, the project was led by the OECD's Directorate for Science, Technology and Innovation. A project interim report containing early policy messages was discussed by the OECD Executive Committee and OECD Council and was presented at the OECD's Ministerial Council Meeting of June 2016.

As this report describes, much policy-relevant research on the changing nature of production remains to be done. Further information on OECD work on this subject will be posted at http://oe.cd/npr-industry. A number of issues raised in this report in connection with digital technologies will also be examined during 2017 and 2018, with new data, in an OECD project titled Going Digital: Making the Transformation Work for Growth and Well-being. *Updated information on this project can be found at www.oecd.org/sti/goingdigital.htm.*

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This publication was edited by Alistair Nolan from the OECD's Directorate for Science Technology and Innovation. Alistair Nolan also wrote Chapter 1 ("The next production revolution: Key issues and policy proposals").

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Christian Reimsbach-Kounatze, from the OECD's Directorate for Science Technology and Innovation, wrote Chapter 2 ("Benefits and challenges of digitalising production").

Thanks are expressed to Robert Cohen, of the Economic Strategy Institute, for case study material provided for Chapter 2.

Chapter 3 ("Bioproduction and the bioeconomy") was prepared by staff from the OECD's Directorate for Science Technology and Innovation.

Steffi Friedrichs, from the OECD's Directorate for Science Technology and Innovation, wrote Chapter 4 ("Tapping nanotechnology's potential to shape the next production revolution").

Chapter 5 ("3D printing and its environmental implications") was authored by Jeremy Faludi, Principal, Faludi Design, University of California, Berkeley and Minneapolis College of Art and Design, with Natasha Cline-Thomas and Shardul Agrawala from the OECD's Environment Directorate. The authors of Chapter 5 would also like to thank Peter Börkey, Andrew Prag, Matthias Kimmel and Elisabetta Cornago for their substantive and editorial contributions to this chapter.

Chapter 6 ("Revolutionising product design and performance with materials innovation") was written by David L. McDowell, Regents' Professor and Carter N. Paden, Jr. Distinguished Chair in Metals Processing, and Executive Director, Institute for Materials, Georgia Institute of Technology.

Chapter 7 ("The next production revolution and institutions for technology diffusion") was authored by Philip Shapira, Manchester Institute of Innovation Research, Alliance Manchester Business School, University of Manchester, and Jan Youtie, Enterprise Innovation Institute, Georgia Institute of Technology.

Chapter 8 ("Public acceptance and emerging production technologies") was written by David Winickoff from the OECD's Directorate for Science Technology and Innovation.

Chapter 9 ("The role of foresight in shaping the next production revolution") was authored by Attila Havas, from the Hungarian Academy of Sciences, and Matthias Weber, from the Austrian Institute of Technology. Extensive input to this chapter was also provided by Michael Keenan from the OECD's Directorate for Science Technology and Innovation. Duncan Cass-Beggs and Joshua Polchar, from the OECD's Strategic Foresight Unit, kindly commented on this chapter.

Chapter 10 ("An international review of emerging manufacturing R&D priorities and policies for the next production revolution") was authored by Dr Eoin O'Sullivan, Director, Centre for Science, Technology & Innovation Policy (CSTI), Institute for Manufacturing (IfM), University of Cambridge, and Dr Carlos López-Gómez Head, Policy Links Unit, Institute for Manufacturing (IfM), Education and Consulting Services, University of Cambridge.

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Chapter 12 ("China and the next production revolution") was authored by Qian Dai, Programme Officer, Department of International Cooperation, Ministry of Science and Technology of China, and Consultant with the OECD's Directorate for Science, Technology and Innovation.

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Many OECD staff contributed to this work. Alistair Nolan managed the project, under the guidance of Dominique Guellec, Head of the Science and Technology Policy Division. Dominique Guellec provided substantive input to all chapters in this report and authored the box on intellectual property in Chapter 1. Andrew Wyckoff, Director, Directorate for Science, Technology and Innovation, and Dirk Pilat, Deputy-Director, provided comments and guidance throughout. This publication also draws on the research and observations of other OECD colleagues, including (in alphabetical order): Koen de Backer, Sarah Box, Stuart Elliott (now with the US National Academy of Sciences), Stéphanie Jamet, Nick Johnstone, Carlo Menon and Mariagrazia Squicciarini. During an internship with the OECD, Nicolas Trausch provided excellent support in reviewing research on automation and employment.

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Executive summary

The next production revolution will occur because of a confluence of technologies. These range from a variety of digital technologies (e.g. 3D printing, the Internet of Things, advanced robotics) and new materials (e.g. bio- or nano-based) to new processes (e.g. data-driven production, artificial intelligence, synthetic biology). This report examines the economic and policy ramifications of a set of technologies likely to be important for production over the near term (to around 2030). As these technologies transform production, they will have far-reaching consequences for productivity, employment, skills, income distribution, trade, well-being and the environment.

Productivity and labour market changes

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 growth of technology-intensive production work. 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 future adjustments are unknown. But resilience and prosperity will be more likely in countries with forward-looking policies, better functioning institutions, better educated and informed citizens, and critical technological capabilities in a number of sectors.

Command over new production technologies also promises greener production, safer jobs (with some hazardous work performed by robots), new and more customised goods and services, and faster productivity growth. Indeed, the technologies considered in this report, from information and communication technologies 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 those firms, many potential applications are underused.

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. The past has seen unrealistic enthusiasm regarding timelines for the delivery of important production technologies.

While new technologies will create jobs through a number of channels, and productivity-raising technologies will benefit the economy overall, the associated adjustments could be significant. Hardship could affect many if labour displacement were to occur in a major sector, or in many sectors simultaneously. Policy makers need to monitor and actively manage the adjustments, e.g. through forward-looking policies on skills, labour mobility and regional development.

Knowledge, technology and skills diffusion

Diffusion of the technologies must include not only the hardware, but also the complementary intangible investments and know-how needed to fully exploit 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 facilitate growth for successful firms is critical. New firms will introduce many of the new production technologies.

Effective institutions dedicated to technology diffusion can help. Especially among small and medium-sized enterprises (SMEs), a major challenge will be the digital transformation of firms which were not born digital. 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.

Rapid technological change will challenge the adequacy of skills and training systems. Some new production technologies raise the importance of interdisciplinary 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, so 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 strong generic skills – such as literacy, numeracy and problem solving – throughout the population, in part because generic skills are a basis for learning fast-changing specific skills.

Investments in data and science

Data will be central to 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 are needed 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.

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. The complexity of many emerging production technologies exceeds the research capacities of even the largest individual firms, necessitating a spectrum of public-private research partnerships. Many of the research challenges critical to the next production revolution are also multidisciplinary. Evaluation metrics for research programmes need to properly incentivise multidisciplinary research, research scale-up and linkages across stakeholders.

Trust and long-term thinking

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. Policy makers and institutions should voice realistic expectations about technologies and duly acknowledge uncertainties. Science

advice should be seen to be unbiased and trustworthy. Public deliberation can also help to build understanding between scientific communities and the public.

Foresight processes, if applied appropriately, can support policy making during times of technological and socio-economic change. With participatory methods, stakeholders can be mobilised to develop shared views about the future, and negotiate and agree on joint actions. Foresight processes can bring benefits in themselves, such as strengthened stakeholder networks and improved co-ordination across policy domains.

Finally, 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 required on a variety of new risks and challenges that emerging technologies create, and how policy priorities might need to evolve, in fields as diverse as the intellectual property system, competition and trade policies, and the distributional implications of future production.

List of acronyms, abbreviations and units of measure

ABS	Acrylonitrile butadiene styrene
AFFOA	Advanced Functional Fabrics of America
AFRC	Advanced Forming Research Centre
AI	Artificial intelligence
AIDS	Acquired immune deficiency syndrome
AIM	Accelerated Insertion of Materials
AMNPO	Advanced Manufacturing National Program Office (United States)
AMP	Advanced Manufacturing Partnership
AMRC	Advanced Manufacturing Research Centre
ANSSI	Agence nationale de la sécurité des systèmes d'information
API	Application programming interface
ARM	Advanced Robotics Manufacturing
ARMI	Advanced Regenerative Manufacturing Institute
ASEAN	Association of Southeast Asian Nations
ASCPM	Advanced Sensing, Control, and Platforms for Manufacturing
ATE	Advanced Technology Education
ATI	Aerospace Technology Institute
ATJ	Alcohol-to-jet
ATP	Advanced Technology Programme
BDC	Business Development Bank of Canada
BEA	Bureau of Economic Analysis (United States)
BLS	Bureau of Labor Statistics (United States)
BMBF	Federal Ministry of Education and Research (Germany)
BMS	Business management system
BRICS	Biological Robustness in Complex Settings
BRIICS	Brazil, the Russian Federation, India, Indonesia, China and South Africa
BSE	Bovine spongiform encephalopathy
CAD	Computer-aided design
CAGR	Compound annual growth rate
CASA	Center for Applied Simulation and Analytics
CCEMC	Climate Change and Emissions Management Corporation
CCEMF	Climate Change and Emissions Management Fund
CEO	Chief executive officer
CER	Comparative effectiveness research
CES	Current Employment Statistics
CFRP	Carbon fibre-reinforced polymer
CIRP	International Academy for Production Engineering (France)
CLA	Contributor License Agreement

CLAD	Construction laser additive directe
CLEEN	Cluster for Energy and Environment (Finland)
CLIP	Continuous liquid interface production
CMOS	Complementary metal oxide semiconductor
CNC	Computer-numeric-control
CNN	Convolutional and deep neural network
CNT	Carbon nanotube
COI	Centers of Innovation
COMAC	Commercial Aircraft Corporation of China
CPI	Centre for Process Innovation
CPPCC	Chinese People's Political Consultative Conference
CPU	Central processing unit
CREATE	Campus for Research Excellence and Technological Enterprise
CRMI	China Regenerative Medicine International
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSIS	Center for Strategic and International Studies
CSTI	Centre for Science, Technology and Innovation
DARPA	Defense Advanced Research Projects Agency (United States)
DDI	Data-driven innovation
DFE	Design for environment practices
DFG	German Research Foundation
DLP	Digital light processing
DMD	Direct metal deposition
DMDII	Digital Manufacturing and Design Innovation Institute
DMLS	Direct metal laser sintering
DNA	Deoxyribonucleic acid
DNN	Deep neural network
DT	Data technology
EC	Ethical concern
EDF	Electricité de France
EEMS	Exploiting the Electromagnetic Spectrum
EERE	Energy Efficiency and Renewable Energy
EFFRA	European Factories of the Future Association
EFMN	European Foresight Monitoring Network
EFSA	European Food Safety Authority
EIB	European Investment Bank
ELSI	Ethical, legal, and social issue
EPEAT	Electronic Product Environmental Assessment Tool
EPO	European Patent Office
EPR	Extended Producer Responsibility
ERP	Enterprise resource planning
ERPP	Environmentally responsible public procurement
ERS	Economic Research Service
ESRC	Economic and Social Research Council
EU	European Union
FAQ	Frequently asked question
FDA	Food and Drug Administration (United States)

FDI	Foreign direct investment
FDM	Fused deposition modelling
FFF	Fused filament fabrication
FLAMEL	From Learning, Analytics, and Materials to Entrepreneurship and Leadership
FMD	Floating Mobile Data
FoF	Fund of Funds
FOREN	Foresight Regional Development Network
FYP	Five-Year Plan
g/cm^3	Grammes per square centimetre
GBAORD	Government Budget Appropriations or Outlays for Research and Development
GDP	Gross domestic product
GHG	Greenhouse gas
GIS	Geographic information system
GM	Genetically modified
GMC	Genetic modification of crops
GMO	Genetically modified organism
GNSS	Global navigation satellite system
GPS	Global positioning system
GPT	General-purpose technology
GPU	Graphics processing unit
GVA	Gross value-added
GVC	Global value chain
HFEA	Human Fertilisation and Embryology Authority (United Kingdom)
HGP	Human Genome Project
HIT	Human intelligence task
HMIS	Hazardous Materials Identification System
HND	Higher National Diplomas
HVM	High Value Manufacturing
IaaS	Infrastructure-as-a-service
IACMI	Institute for Advanced Composites Manufacturing Innovation
IAR	Industries and Agro-Resources
ICME	Integrated Computational Materials Engineering
ICT	Information and communication technology
IDC	International Data Corporation
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IMF	International Monetary Fund
IMSI	International mobile subscriber identity
IoT	Internet of Things
IP	Intellectual property
IPO	Intellectual Property Office (United States)
IPR	Intellectual property right
IR	Industrial robot
IRAP	Industrial Research Assistance Program
IT	Information technology
ITO	Indium tin oxide
IVF	In vitro fertilisation

JBPA	Japan BioPlastics Association
JRA	Junior Research Associate
KAIST	Korea Advanced Institute of Science and Technology
KBC	Knowledge-based capital
KET	Key Enabling Technology
KPI	Key performance indicator
KRIBB	Korea Research Institute of Bioscience & Biotechnology
KTN	Knowledge Transfer Network
km	Kilometre
kV	Kilovolt
LBNL	Lawrence Berkeley National Laboratory
LCA	Life-cycle analysis
LCIA	Life-cycle impact assessment
LEED	Leadership in Energy and Environmental Design
LIFT	Lightweight Innovations for Tomorrow
LLNL	Lawrence Livermore National Laboratory
M&A	Mergers and acquisition
MAFF	Ministry of Agriculture, Forestry and Fisheries (Japan)
MAPI	Manufacturers' Association for Productivity and Investment
MBA	Masters of business administration
MEP	Manufacturing Extension Partnership
MES	Manufacturing execution system
MGI	Materials Genome Initiative
MII	Manufacturing innovation institute
MIT	Massachusetts Institute of Technology
MJ/kg	Megajoule per kilogramme
MOOC	Massive open online course
MPa	Megapascal
MTA	Manufacturing technology area
MTC	Manufacturing Technology Centre
NACFAM	National Council for Advanced Manufacturing
NAE	National Academy of Engineering (United States)
NAMII	National Additive Manufacturing Innovation Institute
NAMRC	Nuclear Advanced Manufacturing Research Centre
NASA	National Aeronautics and Space Administration (United States)
NASS	National Agricultural Statistical Service (United States)
NC	North Carolina
NCC	National Composites Centre
NCIIA	National Collegiate Inventors and Innovators Alliance (United States)
NEC	National Economic Council (United States)
NFTTC	National Fund for Technology Transfer and Commercialization (China)
NGO	Non-governmental organisation
NIFU	Nordic Institute for Studies in Innovation, Research and Education (Norway)
NIMS	National Institute for Materials Science (Japan)
NISE	Nanoscale Informal Science Education
NIST	National Institute of Standards and Technology (United States)
nm	Nanometre

NNI	National Nanotechnology Initiative (United States)
NNMI	National Network for Manufacturing Innovation (United States)
NPC	National People's Congress (China)
NRC	National Research Council (Canada)
NREL	National Renewable Energy Laboratory (United States)
NSF	National Science Foundation (United States)
NSTC	National Science and Technology Council (United States)
NTU	Nanyang Technological University
NUS	National University of Singapore
OEE	Overall equipment effectiveness
OEM	Original equipment manufacturer
OpenKIM	Open Knowledgebase of Interatomic Models
OpenMTA	Open Material Transfer Agreement
OSS	Open-source software
OSTP	Office of Science and Technology Policy (United States)
PaaS	Platform-as-a-service
PACITA	Parliaments and Civil Society in Technology Assessment
PBH	Power by the hour
PCAST	Penetration of advanced manufacturing technologies
PEA	Printed Electronics Arena
PESTLE	Political, economic, social, technological, legal and environmental
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoate
PIAAC	Programme for the International Assessment of Adult Competencies
PIC	Photonics-integrated circuit
PIE	Production in the Innovation Economy
PISA	Programme for International Student Assessment
PLC	Programmable logic controller
PPP	Public-private partnership
PTC	Production tax credit
PV	Photovoltaic
R&D	Research and development
RAM	Roadmap for Additive Manufacturing
RAPID	Rapid Advancement in Process Intensification Deployment
RCT	Randomised control trial
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
REMADE	Reducing Embodied Energy and Decreasing Emissions
RFID	Radio-frequency identification
RoHS	Restriction of Hazardous Substances
ROI	Return on an investment
RRI	Responsible research and innovation
RTO	Research and technology organisation
S&T	Science and technology
SaaS	Software-as-a-service
SAM	Subcommittee on Advanced Manufacturing
SBIR	Small Business Innovation Research
SCADA	Supervisory control and data acquisition

SCM	Supply chain management
SiN	Silicon nitride
SIP	Strategic Innovation Promotion Program
SLA	Stereolithography
SLM	Selective laser melting
SLS	Selective laser sintering
SMEs	Small and medium-sized enterprises
SOE	State-owned enterprise
SRG	Steel Research Group
SSRN	Social Science Research Network
STEM	Science, technology, engineering and mathematics
STI	Science, technology and innovation
STM	Scanning tunnelling microscope
SWOT	Strengths, weaknesses, opportunities and threats
TEP	Technology Foresight Programme
TRL	Technology readiness level
UN	United Nations
UQ	Uncertainty quantification
USB	Universal serial bus
USDA	US Department of Agriculture
US DoD	US Department of Defense
US DoE	US Department of Energy
USPTO	US Patent Office
UV	Ultraviolet
VIDM	Visualization, informatics and digital manufacturing
VOC	Volatile organic compound
WBDF	Water-based digital fabrication
WEEE	Waste electrical and electronic equipment
WIP	Work-in-progress
WIPO	World Intellectual Property Organization
WTO	World Trade Organization

The Next Production Revolution
Implications for Governments and Business
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Chapter 1

The next production revolution: Key issues and policy proposals

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

Introduction

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

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

This report has a technological focus

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

A technological perspective also introduces an appreciation of the importance of some fields of government action which are not always central in micro-economic analyses of productivity and growth. Cases in point, discussed in this report, include: decisions on the composition of public support for manufacturing R&D and how allocation choices might increase impact and efficiency; the design and resourcing of, and performance metrics used for, institutions that diffuse technology; the operation of public-private research partnerships; the benefits of sector-specific understanding of technical change; how the increasing complexity and digital foundation of many production systems creates new interdependencies between firms, technologies and a variety of institutions (such as providers

of resources for supercomputing); the evolution of technology-specific skill needs; the processes that governments use to prepare for the future; and how policy can shape public attitudes to technology, which can itself affect the course of technology adoption. Insights on these and other policy issues can complement standard analyses of firms and markets. Furthermore, accounts of past episodes of technological change in production, as sketched in a subsection of this chapter, can help to inform responses to today's technological disruptions.

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

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

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

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

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

National initiatives for advanced manufacturing have proliferated in recent years. Germany's Industry 4.0 initiative ("Plattform Industrie 4.0"), the National Network for Manufacturing Innovation in the United States, Japan's Robot Strategy, the People's Republic of China's (hereafter "China") Made in China 2025 and Internet Plus initiatives are just some examples. As Chapters 9 and 10 describe, many countries have prepared

national manufacturing foresight studies and strategies, as well as in-depth roadmaps, for priority manufacturing technologies. And manufacturing has grown as a theme in recent national research and innovation strategies.

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

The structure of the report and the scope of this chapter

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

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

Productivity and the technologies of the next production revolution

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

However, many OECD countries have experienced faltering productivity growth in recent years. Some high-profile commentators claim that slower productivity reflects a general

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

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

Emerging technologies affect productivity through many channels

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

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

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

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

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

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

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

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

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

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

Work, automation and the new technologies of production

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

Concerns over technology-based unemployment have a long history. Even before the Luddite protests against the mechanisation of textiles manufacture in early nineteenth-century England, many production technologies have raised fears of labour market disruption. The term "technological unemployment" was coined by John Maynard Keynes in 1930 (Keynes, 2009). In 1961, in the United States, the Kennedy Administration created an Office of Automation and Manpower, citing "the major domestic challenge of the Sixties: to maintain full employment at a time when automation, of course, is replacing men" (quoted

in Miller and Atkinson, 2013). More recently, workers polled in the United States in the 1970s and 1980s were constantly concerned about automation (Miller and Atkinson, 2013). Most of these fears have turned out to be unjustified. Nevertheless, many commentators argue that aspects of today's digital technology give such fears a new foundation.

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

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

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

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

Technological development also creates jobs through a number of channels

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

is sensitive to changes in price, a small decline in the price of the firm's output could lead to an increase in the firm's workforce (Autor, 2015).

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

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

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

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

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

But adjustment might be painful

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

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

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

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

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

Policy makers need to monitor and prepare for adjustment processes

This section has highlighted historical evidence that productivity-raising technologies lead to labour market adjustments at higher levels of income. It has also underscored that

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

Digital technologies and future production

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

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

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

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

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

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

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

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

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

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

Barriers to ICT diffusion, interoperability and standards should be lowered

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

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

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

Addressing emerging risks and uncertainties: Main policy considerations

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

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

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

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

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

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

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

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

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

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

Bioproduction and the bioeconomy

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

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

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

Strategies to expand biorefining must address the sustainability of the biomass used. Governments can help to create sustainable supply chains for bio-based production. In particular, governments should urgently support efforts to develop comprehensive or standard definitions of sustainability (as regards feedstocks), tools for measuring

sustainability, and international agreements on the indicators required to drive data collection and measurement (Bosch, van de Pol and Philp, 2015). Furthermore, environmental performance standards are needed for bio-based materials. Such standards are indispensable because most bio-based products are not currently cost-competitive with petrochemicals, and because sustainability criteria for bio-based products are often demanded by regulators.

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

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

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

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

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

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

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

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

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

Bioproduction and industrial biotechnology: Main policy considerations

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

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

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

Governments should focus on three objectives as regards regulations:

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

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

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

Tapping the potential of nanotechnology

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

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

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

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

Nanotechnology: Main policy considerations

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

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

Nanotechnology: Main policy considerations *(cont.)*

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

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

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

3D printing, production and the environment

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

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

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

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

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

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

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

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

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

3D printing and sustainability: Main policy considerations

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

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

New materials and the next production revolution

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

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

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

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

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

New materials and the next production revolution: Main policy considerations

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

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

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

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

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

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

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

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

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

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

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

Diffusion is affected by national and international conditions

Several factors, operating at national and international levels, shape the diffusion process. These include: i) global connections via trade – which is a vehicle for technology diffusion and an incentive for technology adoption – and foreign direct investment (FDI); ii) the international mobility of skilled labour; iii) connections and knowledge exchange within national economies, such as the interaction between scientific institutions and businesses; iv) the existence and development of standards (the semiconductor industry,

for example, uses over 1 000 standards [Tassey, 2014]); vi) the extent of businesses' complementary intangible investments in R&D, skills, managerial capabilities and other forms of knowledge-based capital (OECD, 2015c); and vii) the efficiency of the processes by which firms can attract the resources they need to grow. If firms which could lead the next production revolution are unable to attract the human and financial resources to grow, the future development and diffusion of technology will be stunted.

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

Beyond framework conditions, institutions for technology diffusion can be effective

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

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

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

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

as the hub of a network of company and university organisations to develop standards and prototypes in many areas, such as 3D printing and digital manufacturing and design (see also Chapter 11 for a comprehensive examination of Manufacturing USA).

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

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

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

The diffusion of new production technologies: Main policy considerations

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

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

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

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

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

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

Public acceptance and new technologies

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

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

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

Other technologies addressed in this report have raised public concerns of different kinds. Some considerations have to do with risk, such as how nanotechnologies might affect human health (see Chapter 4). Government programmes to collect and use big data have also raised public concerns. For example, in the United Kingdom, failure to address privacy and access questions triggered a major public controversy among clinical physicians, disease

advocacy groups and the larger public, undermining trust in central health authorities. The next production revolution could raise societal issues not seen before. For example, as machine autonomy develops, who will be responsible for the outcomes that machines give rise to, and how will control be exercised?

Public acceptance and new technologies: Main policy considerations

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

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

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

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

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

The role of foresight in shaping the next production revolution

As Attila Havas and Matthias Weber describe in Chapter 9, greater foresight in science and technology is sought by most governments. A goal of the America Competes Act, for example, is the identification of emerging and innovative fields. Better anticipation of

trends could clearly assist policy development and the allocation of research funds and other resources.

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

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

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

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

Foresight processes: Main policy considerations

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

Foresight processes have the potential to enlarge and renew the framing of policy issues. In a connected way, foresight can help to induce organisational innovations. Government bodies tend to be organised by rigidly demarcated policy domains. Organisational structures

can lag behind fast-changing scientific and technological fields. In such cases, it can be difficult to find a proper place for cross-cutting research or for new ways of directing research (e.g. in shifting from science and technology-led research to societal challenge-driven research). Government bodies can also be insular, with the same participants sometimes repeatedly involved in decision making. Foresight processes can help to offset the effects of such conditions.

Sound science and R&D policies are important

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

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

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

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

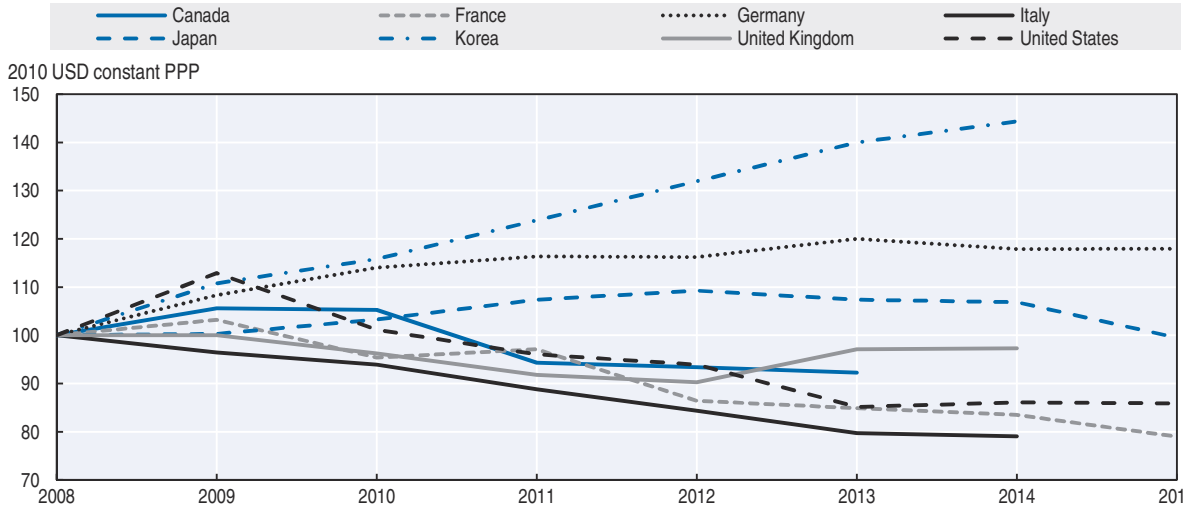
In examining new production technologies, this report has identified many possible targets for government supported R&D and commercialisation. These range from quantum computing (Chapter 2), to advancing the use of data analytics and digital technologies in metabolic engineering (Chapter 3), to the development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

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

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

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

Index: 2008 = 100



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

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

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

Many of the critical research challenges are multidisciplinary and systemic

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

key innovation system actors, including more explicit requirements for interdisciplinary and inter-institutional collaborations, and providing new types of innovation infrastructure (tools, enabling technologies and facilities) to support convergence and scale-up.

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

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

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

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

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

industrial researchers, but also designers, suppliers, equipment suppliers, shop floor technicians, and users.

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

The rise of advanced manufacturing institutes in the United States

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

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

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

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

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

Technological change also raises challenges for the IP system

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

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

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

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

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

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

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

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

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

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

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

Education and skills systems need constant attention

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

Policies that improve the efficiency of skills matching in labour markets are essential and support productivity (OECD, 2015c). How new production technologies relate to the process of skills matching may primarily concern a possible increase in the magnitude or speed of change. As previously noted, the pace and scope of technology-driven labour market changes is uncertain. But many types of work are predicted to decline or disappear. For example, sensor-based predictive maintenance, self-organising production and 3D printing of complex objects could eliminate jobs, respectively, for traditional service technicians, production planners, and workers in assembly and inventory management. But those same technology uses could also give rise to new occupations. For example, predictive maintenance will bring novel work in system design and data science. Self-

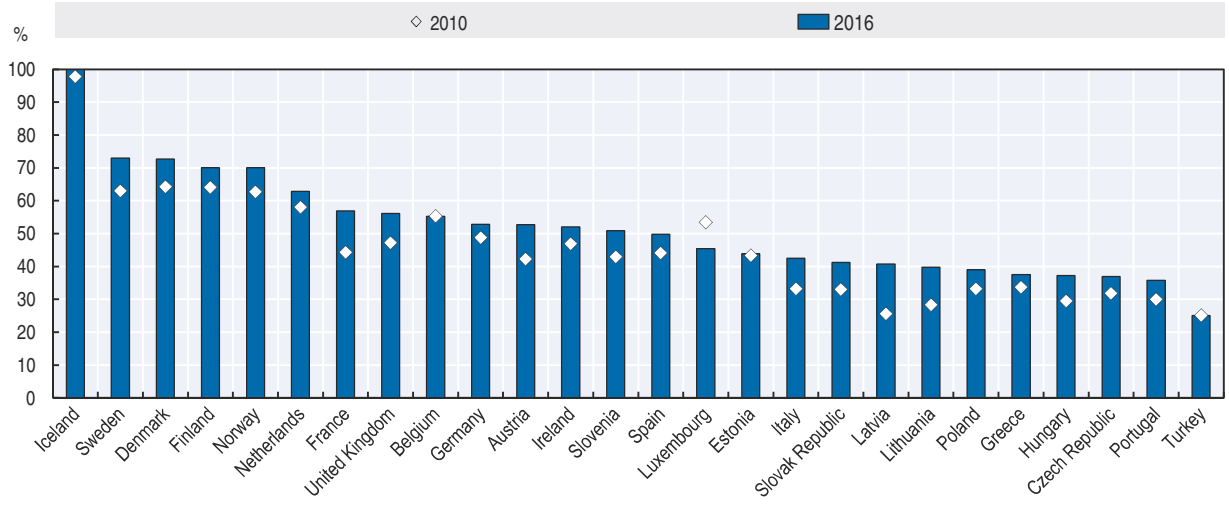
organising production will require specialised data modellers. And 3D printing will create jobs for computer-aided designers. As robots are deployed more widely, demand will rise for robot co-ordinators to oversee robots and respond to malfunctions. A particularly highly demanded new job could be that of industrial data scientist (Lorentz et al., 2015).

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

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

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

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



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

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

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

Some new production technologies raise the importance of interdisciplinary education and research. For example, progress in synthetic biology requires interaction among biologists, physicists, synthetic chemists and computer programmers. Achieving interdisciplinarity is not a new challenge. Solutions on the supply side are likely to emerge from the efforts of education and research institutions themselves and from the effects of inter-institutional competition. However, policy might also help. For example, peer review practices bear on the way that public agencies allocate funding for multidisciplinary

research. But more needs to be known about the practices adopted across research institutions, teams and departments – private and public – which enable interdisciplinary education and research. Policy makers could seek to replicate, where appropriate, the approaches of institutions that have proven successful in fostering interdisciplinary research, such as Stanford's Bio-X.

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

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

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

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

The next production revolution may bring changes to labour market policies

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

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

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

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

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

The importance of geography-specific policies could also rise

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

Policy needs long-term thinking

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

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

China and the next production revolution

In Chapter 12, Qian Dai examines recent and projected developments in production in China. Manufacturing is a foundation of China's economy, and China is now the largest contributor to global manufacturing value-added. China's weight in global manufacturing,

combined with the country's goal of increasing the knowledge content of domestic production, has many implications for itself and for production elsewhere in the world.

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

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

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

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

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

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

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

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

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

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

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

The next production revolution and global value chains (GVCs)

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

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

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

Labour-intensive industries which predominate in many developing countries, such as garments, shoes and leather, furniture, textiles and food, could be less susceptible to change, since many processes in these industries are not yet fully (or economically) automated. Other industries, such as the electrical and electronics and machinery sectors,

are likely to be significantly affected, particularly if wages are growing, because of their high potential for automation. In other sectors, such as automotive manufacture, adopting new production technologies is expected to be determined not so much by wages or the potential for automation, but by domestic demand and consumers' growing desire for quality and customisation.

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

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

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

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

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

Conclusion

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

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

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

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

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

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

Notes

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

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

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PART I

Key emerging technologies

PART I

Chapter 2

Benefits and challenges of digitalising production

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This chapter examines how new information and communication technology (ICT) applications – in particular big-data analytics, cloud computing and the Internet of Things (IoT) – enable novel production and organisational processes, and business models, mainly in industrial sectors. The chapter focuses on the productivity implications of new ICT applications in early adopting firms in a number of industries (including automotive and aerospace) but also in traditional sectors such as agriculture. An assessment is provided of policy settings needed to realise the potential productivity and other benefits of digital technologies in production, while mitigating a number of associated risks.

The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Introduction

Digitalisation of the economy and society is progressing rapidly, especially in developed countries. Today, three out of four inhabitants in the OECD area have access to mobile wireless broadband, and up to 95% of all businesses are connected to the Internet. Three-quarters of businesses have an online presence and almost as many engage in e-commerce (OECD, 2015a; 2015b).

Industrial production is undergoing a transformation driven by the conjunction of the increasing interconnection of machines, inventories and goods delivered via the IoT, the capabilities of software embedded in machines, analysis of the large volumes of digital data ("big data") generated by sensors, and the ubiquitous availability of computing power via cloud computing. The resulting transformation has been described by some as "Industry 4.0" (Jasperneite, 2012), the "Industrial Internet" (Bruner, 2013), and "network manufacturing" (Economist Intelligence Unit, 2014). The potential economic benefits of new digital technologies are large. For example, available estimates suggest that the IoT could contribute USD 10 trillion to USD 15 trillion to global gross domestic product (GDP) over the next 20 years (Evans and Anninziata, 2012).

This chapter examines how the conjunction of new digital technologies – in particular big-data analytics, cloud computing and the IoT – enable more customisable goods and services via new production and organisational processes, as well as new business models, mainly in industrial sectors. Based in part on commissioned case study materials, the chapter focuses on the productivity implications of digital technologies in early-adopting firms in a number of industries (including automotive and aerospace) as well as in traditional sectors such as agriculture. It discusses steps that can be taken by traditional firms to successfully transition to digital business models.

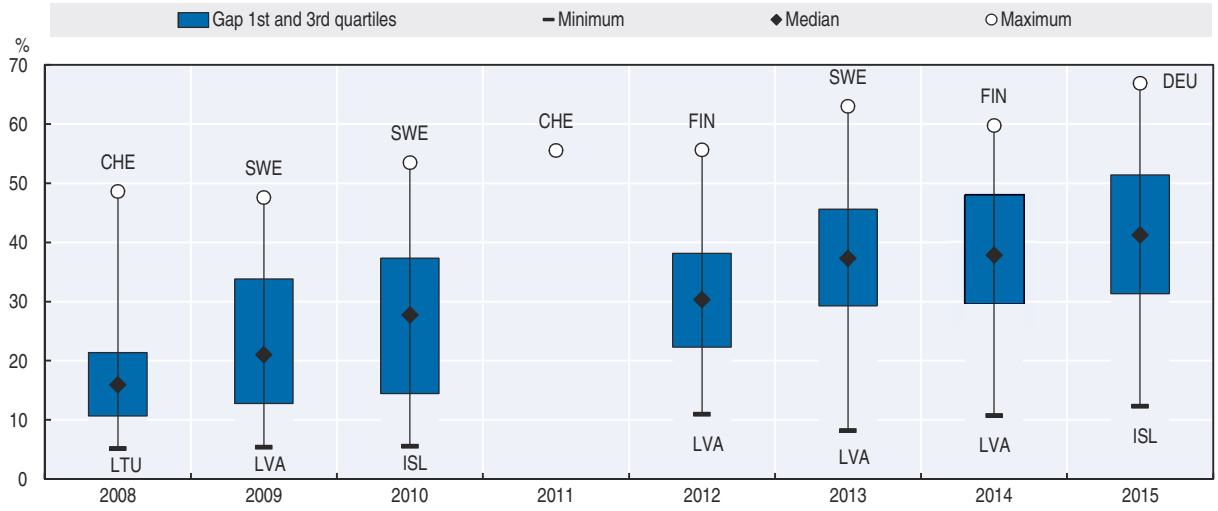
Policy suggestions are described which address the main challenges in digitalising industrial production, including: expanding access to data and critical ICT infrastructures and applications; improving interoperability and supporting the development of standards; using existing frameworks – and where necessary refining these – to reduce a range of emerging uncertainties (related e.g. to liability in the context of automation and ownership in an environment where intangible assets such as data can be critical to value creation); reducing risks in connection with digital security and privacy; and fostering competition in new digital contexts. Underpinning all of the above, the chapter likewise points to the need to develop the skills required for the next production revolution.

Adopting advanced ICTs in production

In manufacturing and agriculture, ICTs are transforming production, as businesses are using advanced ICTs such as enterprise resource planning (ERP) and supply chain management (SCM) software to significantly raise productivity.[1] And the use of such software is growing rapidly. In 2015, for example, in the Netherlands, Finland and Sweden, more than 60% of all manufacturing firms used ERP software. By comparison, in 2009, only

around 40% of manufacturing firms used ERP software in the Netherlands and Finland, and 50% did so in Sweden. And in Germany, already 70% of manufacturers used ERP software in 2015, compared with some 40% in 2009 (Figure 2.1). In contrast, only 40% of all businesses (across all sectors) in these respective countries used ERP software, with the exception of Germany, where the share was 60% in 2015.

Figure 2.1. **Share of manufacturing firms using ERP software, 2008-15**



Note: This figure does not include data for 2011 except for Switzerland. It includes data for Austria, Belgium (except 2008-09,2014-15), Canada (except 2008-10, 2014-15), Czech Republic, Denmark (except 2008-09), Estonia, Finland (except 2008), France (except 2008), Germany (except 2008), Greece (except 2009-14), Hungary, Iceland (except 2008-09), Ireland (except 2008), Italy (except 2008), Korea (except 2008-10), Latvia (except 2008), Lithuania, Luxembourg (except 2008-09), the Netherlands (except 2008), Norway, Poland (except 2009), Portugal (except 2008), Slovak Republic, Slovenia, Spain (except 2008), Sweden (except 2008), Switzerland (except 2009-10, 2012-2015), Turkey (except 2008-09, 2012-15) and the United Kingdom (except 2008).

Source: Based on OECD (2016f), *OECD.Stat*, database, *http://dotstat.oecd.org/index.aspx?DatasetCode=ICT_BUS* (accessed September 2016).

StatLink *http://dx.doi.org/10.1787/888933473741*

Digitalisation promises greater control over production, greater flexibility in the scale and scope of production, and reduced operation costs (see Box 2.1 on the use of manufacturing execution systems [MESs]). In agriculture, for example, farmers generate data which companies such as John Deere and DuPont Pioneer can exploit through new data-driven software services (Noyes, 2014). For example, sensors in John Deere's latest equipment can help farmers manage their fleet of vehicles, reduce tractor downtime and save resource consumption (Big-Data Startups, 2013). The digital transformation of industrial production is also making certain industries more service-like, a trend sometimes described as "servicification" (Lodefalk, 2010). This approach has already been taken by firms such as Rolls-Royce, Boeing, Michelin and John Deere, to name a few (see sections below).

Today the IoT allows manufacturing companies to better monitor the use of their products and thus to provide customised pay-as-you-go services priced using real-time operational data. Rolls-Royce, for example, was a pioneer of this approach, when in the 1980s it stopped selling its jet engines alone, and began selling "power by the hour" – a fixed-cost service package over a fixed term (OECD, 2016b).[2] Data is now also used to monitor and analyse the efficiency of products and is increasingly commercialised as part of new services for existing and potential suppliers and customers. Germany-based Schmitz Cargobull, the world's largest truck body and trailer manufacturer, also uses the IoT to monitor the maintenance, travelling conditions and routes of all its trailers (Chick, Netessine and

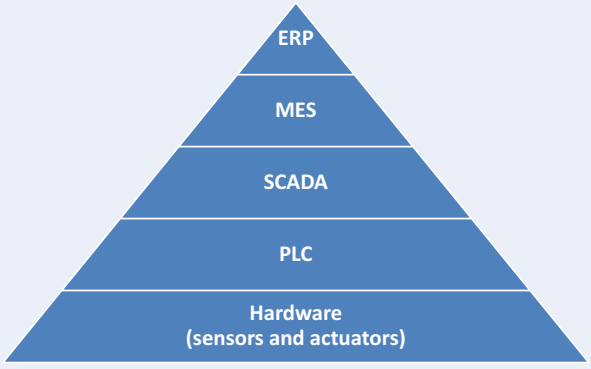
Huchzermeier, 2014). This helps Schmitz Cargobull's customers to minimise usage breakdowns. Energy production equipment manufacturers, as another example, increasingly use sensor data to help their customers optimise contingencies in complex project planning activities (Chick, Netessine and Huchzermeier, 2014).

Box 2.1. **The potential of MESs: The case of MPDV Mikrolab GmbH**

The enormous competitive pressure under which manufacturing companies stand will continue to grow with the ongoing digitalisation of industrial production. Manufacturing firms must be able to react more flexibly and quickly to unexpected changes in order to use all resources as efficiently as possible. These requirements drive companies to use advanced ICTs, not least to master the ever-growing complexity resulting from increasing product diversity and ever-shorter product life cycles and to provide reliable information, ideally in real time, to make better short and long-term decisions.

As the digitalisation of industrial production intensifies, advanced ICTs and in particular MESs, become central in manufacturing companies. MESs are used to manage operations on the shop floor, usually connecting the business ERP system with the shop floor's supervisory control and data acquisition (SCADA) and programmable logic controllers (PLC) systems (Figure 2.2). The scope of a MES can vary from scheduling a small set of critical machines to managing the entire manufacturing process. According to Harris (2017), "The functions of MES programs include: compiling a bill of materials, resource management and scheduling, preparing and dispatching production orders, preparing work-in-progress (WIP) reports and tracking production lots. Advanced systems will also have a product definition library with revision history and can report on production status to an ERP".

Figure 2.2. **Stack of systems used for the automation of industrial production**



Source: OECD, based on Snatkin et al. (2013), "Real time production monitoring system in SME", *http://dx.doi.org/10.3176/eng.2013.1.06*.

Several of the major automation providers such as Emerson, General Electric, Honeywell, Invensys, Rockwell and Siemens offer MES solutions, as do major ERP system vendors such as Microsoft, Oracle, Sage and SAP. These vendors tend to focus on large firms as their main customers. MPDV Mikrolab GmbH, a small and medium-sized enterprise (SME) based in Mosbach, Germany, is one of the leading suppliers of MES with a focus on SMEs. MPDV offers a broad range of field-tested and specialised MES applications to more than 930 firms worldwide, under the HYDRA brand.

Box 2.1. **The potential of MESs: The case of MPDV Mikrolab GmbH** *(cont.)*

MPDV has reported that clients using HYDRA have been able to increase their overall equipment effectiveness (OEE measures how effectively a manufacturing operation is utilised) by more than 15% in the first two years.

Research provides evidence for the benefits of using an MES. Adler et al. (1995), for example, showed that 10% to 30% of the production personnel and support group's time could be reduced with an MES, subject to complementary investments in business process reengineering. Strategic Direction (2004) also shows that MES enable a reduction of overall lead time by around 30%. A more recent study by Nasarwanji et al. (2009) confirmed potential savings in labour overheads. However, the authors also show that these savings start to be realised only after exceeding 80% of the factory's capacity utilisation.

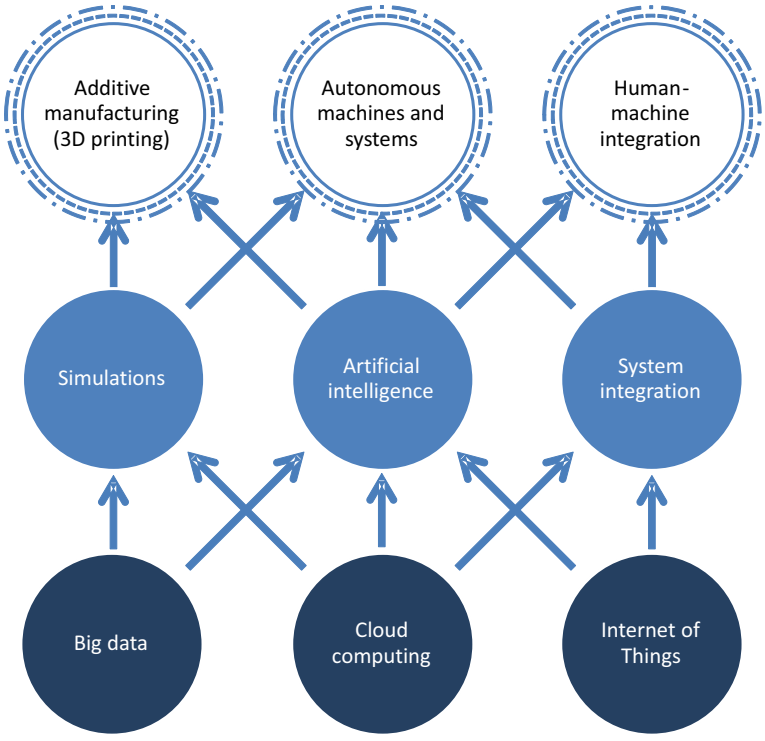
Source: OECD, based on *www.plattform-i40.de/I40/Redaktion/DE/Anwendungsbeispiele/232-mpdv/beitrag-mpdv.html* (accessed 15 January 2017), Adler, D. et al. (1995), "Does a manufacturing execution system reduce the cost of production for bulk pharmaceuticals?"; Nasarwanji, A. et al. (2009), "The impact of manufacturing execution systems on labor overheads", *www.iaeng.org/publication/WCE2009/WCE2009_pp734-737.pdf*; Strategic Direction (2004), "Meeting the manufacturing challenge: Performance advantage of MES", *http://dx.doi.org/10.1108/02580540410567265*, Snatkin, A. et al. (2013), "Real time production monitoring system in SME", *http://dx.doi.org/10.3176/eng.2013.1.06* and Harris, D. (2017), "Compare manufacturing execution systems (MES): Buyer's Guide", *www.softwareadvice.com/manufacturing/execution-systems-comparison/*.

Quantitative evidence on the economic impact of the digital transformation of industry is limited. But estimates from Japan suggest that the use of big data and analytics in some divisions of Japanese manufacturers could lower maintenance costs by almost JPY 5 trillion (corresponding to more than 15% of sales in 2010). More than JPY 50 billion could also be gained in electricity savings (MIC, 2013). Estimates for Germany indicate that the use of advanced ICTs in industry could boost productivity by 5% to 8%. Industrial component manufacturers and automotive companies are expected to achieve the biggest productivity improvements (Rüssmann et al., 2015). Other estimates suggest that "Industry 4.0" could boost value-added in Germany's mechanical, electrical, automotive, chemical, agriculture and ICT sectors by an additional EUR 78 billion (or 15%) by 2025 (BITKOM and Fraunhofer, 2014).[3]

The confluence of digital technologies drives the transformation of industrial production

Two major trends make digital technologies transformational for industrial production: the reduction of the cost of these technologies, enabling their wider diffusion, including to SMEs; and, most importantly, the combination of digital technologies, enabling new types of applications. Figure 2.3 depicts the key ICTs which are enabling the digital transformation of industrial production.[4] The technologies at the bottom of Figure 2.3 enable those at the top, as indicated by the arrows. The technologies at the top of Figure 2.3 (in white), which include additive manufacturing (i.e. 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. In combination, these technologies could one day lead to fully automated production processes, from design to delivery (Box 2.2). The technologies in Figure 2.3, and their applications, are discussed in the following paragraphs.

Figure 2.3. **The confluence of key technologies enabling the industrial digital transformation**



Box 2.2. **A possible manufacturing process in 2025**

In the near future, possibly as early as 2025, manufacturing could become an almost completely autonomous activity. Present-day capabilities suggest that the following hypothetical scenario could be feasible:

A group of designers have created a new device. They show 3D-printed prototypes to potential buyers and, as a result, receive a contract from an overseas retailer. The design, packaging and component list is uploaded to an online marketplace where manufacturers compete for the contracts to create the parts and assemble the device. One contractor wins the contract to assemble the device. This contractor uses cloud-based computer-aided design tools to simulate the design and manufacturing of the device. Machine-learning algorithms test which combination of robots and tools is the most efficient in assembling the device. Some components, such as systems-on-a-chip and sensors, can be sourced from existing manufacturers. Others might have to be specifically created. Robotic devices execute mass production of the components.

All the components and the associated data are then sent to the assembly facility. On the assembly line, the robots in the line retool and arrange themselves. Robotic vehicles move the components across the floor to the correct robot workstations and the robots start to assemble the devices. Every time the robots assemble a device, machine-learning algorithms in the cloud analyse the data and compare these to the simulations, resimulating and establishing whether the process still fits the parameters and whether the process can be optimised. The finished product is boxed by a robot, and the box loaded by another robot onto a self-driving truck, which takes it to the retailer.

Box 2.2. **A possible manufacturing process in 2025** *(cont.)*

At the retailer, robots unload the truck and place the product in the correct warehouse storage location. When the product is ordered, a smaller delivery robot transports it to the customer's front-door. If sales of the product exceed expectations and orders increase from around the world, the designers might need more production capacity. They again turn to the market, with manufacturers in the regions where the product has been ordered competing to produce larger or smaller batches of the product. The results of the earlier machine-learning algorithms are communicated to the successful factories around the world, where different robots assess how to manufacture the product. When a factory has finished producing its order, the robots reorganise and retool for a different product. From the moment the design is finalised, until the product arrives to the customer, no worker has been employed to manufacture the device. Employees monitored the process. However, neither in the plastics moulding, nor the assembly, nor the logistics were humans necessary.

Big-data analytics are transforming all sectors of the economy including traditional sectors

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). However, volume, velocity and variety (the three Vs highlighted as the characteristic of big data) are in continuous flux, as they describe technical properties that evolve with the state-of-the-art in data storage and processing. Others have also suggested a fourth V, for value, which is related to the increasing social and economic value of data (OECD 2013).

The use of big data promises to significantly improve products, processes, organisational methods and markets, a phenomenon referred to as data-driven innovation (DDI) (OECD, 2015b). In manufacturing, data obtained through sensors are used to monitor and analyse the efficiency of machines to optimise their operations and to provide after-sale services, including preventative maintenance. The data are sometimes also used to work with suppliers, and are, in some cases, even commercialised in the form of new services (for example, to optimise production control). In agriculture, geocoded maps of fields and real-time monitoring of every agricultural activity, from seeding to harvesting, are used to raise agricultural productivity. The same sensor data can then be reused and linked with historical and real-time data on weather patterns, soil conditions, fertiliser usage and crop features, to optimise and predict agricultural production. Traditional cultivation methods can be improved and the know-how of skilled farmers formalised and made widely available.

There is still little macroeconomic evidence on the effects of DDI, but available firm-level studies suggest that using DDI raises labour productivity faster than in non-using firms by approximately 5% to 10% (OECD, 2015b). In the United States, Brynjolfsson, Hitt and Kim (2011) estimate that output and productivity in firms that adopt data-driven decision making are 5% to 6% higher than what would be expected given their other investments in, and use of, ICTs. These firms also perform better in terms of asset utilisation, return on equity and market value. A study of 500 firms in the United Kingdom found that firms in the top quartile of online data use are 13% more productive than those in the bottom quartile (Bakhshi, Bravo-Biosca and Mateos-Garcia, 2014). Barua, Mani and Mukherjee (2013) suggest that improving data quality and access by 10% – presenting data more concisely and consistently

across platforms and allowing it to be more easily manipulated – would increase labour productivity by 14% on average, but with significant cross-industry variations.[5] Nevertheless, big data is still mainly used in the ICT sector, particularly in Internet services firms. According to Tambe (2014), for example, only 30% of Hadoop investments come from non-ICT sectors, including, in particular, in finance, transportation, utilities, retail, health care, pharmaceuticals and biotechnology firms. But manufacturing is becoming increasingly data-intensive (see McKinsey Global Institute [2011]).

In agriculture, the use of data and analytics (i.e. precision agriculture) provides productivity gains by optimising the use of agriculture-related resources. These include, but are not limited to, savings on seed, fertiliser and irrigation as well as farmers' savings in time (Box 2.3). Depending on the savings considered, estimates of the productivity effect vary. One estimate, for example, suggests that in farming corn in the United States, precision agriculture could improve yields by 5 to 10 bushels per acre, increasing profit by around USD 100 per acre (at a time when gross revenue minus non-land costs stood at about USD 350 per acre) (Noyes, 2014). Extrapolating, one could estimate economic benefits for the United States from precision agriculture to be around USD 12 billion annually. This represents about 7% of the total value-added of USD 177 billion contributed by farms to the GDP of the United States.[6] When excluding farmers' savings in time, more modest benefits per acre from precision farming have been estimated. Schimmelpfennig and Ebel (2016), for example, presented an estimate of increased profits of USD 14.50 per acre. A similar study by Professor Craig Smith of Fort Hays State University, Kansas, focused on the same sources of increased efficiency from precision agriculture for different size farms.[7] This work focused on precision agriculture's "automatic row and section control, which uses a global positioning system (GPS) to prevent excess application of crop inputs, such as fertilizer and crop protection chemicals." (John Deere, 2015). Farmers' cost savings for the corn fields, similar to the large-row-crop farms, evaluated above, were from USD 1 to USD 15 an acre.

Box 2.3. **Precision agriculture with big data: The case of John Deere**

Precision agriculture provides farmers with near real-time analysis of key data about their fields. John Deere entered this business, initially with yield mapping and simple variable rate controls, and later with automated guidance technology (AutoTrac[1]). Those early products have since been enhanced by creating automated farm vehicles that communicate with each other. From the beginning, John Deere built on GPS location data. It then developed initial "wired" capabilities to connect farm machines to each other and to the MyJohnDeere (MJD) Operations Center, which is described by the company as "a set of online tools that provides information about a farm, when and where farmers need it." (Arthur, 2016).

To support vehicles in the field, John Deere developed remote wireless management for farm equipment. It used interconnected satellite and cellular ground-based communications networks, proprietary radio and Wi-Fi. This helped Deere reduce the time to harvest crops or complete other tasks. For example, its self-propelled, programmable vehicles could plant or harvest about 500 to 600 acres a day when used in groups of two or more vehicles, rather than the usual 100 to 150 acres that a single farmer could do alone. One enhancement Deere introduced for planting was to use its Exact-Emerge planter and AutoTrac to expand the number of acres that could be planted under optimal conditions. With the enhanced planter and tracking system, the number of acres planted could increase from 600 to more than 800 per day. For harvesting, operations would also be much more efficient if the vehicles used incorporated AutoTrac.

Box 2.3. **Precision agriculture with big data: The case of John Deere** *(cont.)*

Utilising a combination of sensors and GPS, Deere's tractors not only drive themselves, they also utilise analytic systems. These systems permit vehicles to do planting, watering and harvesting with accuracy to two centimetres. These systems can also communicate with each other. Deere has estimated that it has more than 100 000 connected machines around the world. Tractor cabs also offer Wi-Fi communication with mobile and other on-board sensor systems, as well as other radios for mobile communications with other vehicles. This helps farmers synchronise operations and share data with other farmers.

Using the interconnected devices and smart sensors in this communications network, John Deere combined basic and performance data from its machines with in-field, geo-referenced data to enhance data analytics. Once systems capture these combined data and send them to Deere's Operations Center, they are incorporated into a more extensive database that also includes environmental information. Deere can combine information from the farmer with data about the environmental condition (including weather and climate data and data about the soil quality) as well as data about real yields. This helps farmers identify the sections of their land that are more productive. John Deere's use of data analytics helps farmers optimise crop yield, because "farmers can use the data to decide what and where each piece of equipment will plant, fertilise, spray and harvest … for an area as small as one by three metres." (Jahangir Mohammed, 2014).

In 2011, John Deere cemented its long-term strategy to focus on integrated data-driven products. The new focus also emphasised an increase in research and development (R&D) investments to 5.5% of net sales, compared to its competitors' R&D investments of 4% to 5%. The focus on innovation helped Deere continue the 5% compound annual growth rate for employee productivity (measured by sales per employee) achieved over the past 30 years (Deere & Company, 2016). To buttress its capabilities in this area, John Deere also acquired a number of companies that have pioneered precision agriculture, such as Precision Planting (Agweb, 2015), a leading planting technology firm that also supplies hardware and sensors, and Monosem, a France-based planter equipment manufacturer. John Deere is also hiring data scientists to improve its ability to analyse big data. These professionals will:

- Identify relevant data, sources and applications.
- Utilise big-data mining techniques such as pattern detection, graph analysis, and statistical analyses to "discover hidden insights".
- Implement collection processes as well as develop infrastructure and frameworks to support analyses.
- Use parallel computation languages to implement applications.

Substantial market growth is forecast for John Deere and similar firms offering farmers self-propelled vehicles and precision agriculture systems. Such forecasts predict that the global precision farming market will expand by USD 4.92 billion by 2020. This represents a compound annual growth rate (CAGR) of almost 12% between 2015 and 2020. At the present time, precision farming globally represents a USD 2.8 billion market (Mordor Intelligence, 2016). The US market accounts for roughly USD 1 billion to USD 1.2 billion of these sales annually. Using estimates for the large-row-crop, corn and soybean farms, where about two-thirds of acreage is subject to precision agriculture, it is conservatively estimated that John Deere's sales of precision agriculture are about one-quarter of the United States market total, or USD 250 million to USD 350 million.[2]

Box 2.3. **Precision agriculture with big data: The case of John Deere** *(cont.)*

1. AutoTrac Vision uses a front-mounted camera to see early-season corn, soybeans and cotton at least four to six inches high. It helps farmers avoid damaging crops with sprayer wheels even the planter is misaligned (John Deere, 2017).
2. According to a market forecast, this market would include a number of technologies that are integrated, essentially guidance systems, remote sensing and Variable Rate Technologies. The largest would be guidance systems with GPS, geographic information systems (GIS) and global navigation satellite systems (GNSS) systems, etc. The market forecast finds that various monitoring and mapping systems would be more important and that software applications, i.e. those applications for crop, farm and weather management, would grow faster during the forecast period (see Mordor Intelligence [2016]).

Cloud computing enhances the agility, scalability, and interoperability of businesses

Cloud computing allows computing resources to be accessed in a flexible on-demand way with low management effort (OECD, 2014a).[8] Many high-potential industrial applications, such as autonomous machines and systems, and complex simulation, are very computationally intensive and therefore require supercomputers. Cloud computing has played a significant role in increasing the availability and capacity, and lowering the cost, of highly scalable computing resources, in particular for start-ups and SMEs. This is because cloud computing services can be easily scaled up or down, be used on demand, and paid for either per user or by capacity used. Cloud computing services can take the form of software (software-as-a-service [SaaS]) or be extended to platforms (platform-as-a-service [PaaS]) or infrastructure (infrastructure-as-a-service), and may be deployed privately (for exclusive use), publicly (open to the general public), or under a hybrid format (a mix of the two former arrangements).Businesses mainly adopt cloud computing to increase business agility and decrease ICT investment costs. A survey by the cloud computing technology provider VMware (2011) shows that 57% of all respondents point to accelerating the execution of projects and improving customer experience as the most frequent reasons for adopting cloud computing, followed by the ability to rapidly adapt to market opportunities (56%) and the ability to scale costs (55%). In some countries, such as Austria, Iceland, the Netherlands and Norway, however, a large majority of businesses still consider that benefits linked to the reduction of ICT costs are not noticeable, or are limited (OECD, 2015a).

In addition, the ubiquity of cloud computing makes it the ideal platform for data sharing across sites and company boundaries, thereby enabling system integration within organisations (vertical integration) and between organisations (horizontal integration). Today many businesses compete on how well they can combine their goods and services. This highlights not only the emerging importance of the IoT as a platform for integrating physical objects with the Internet (see section below), but also the importance of the cloud as a platform for service integration. Without a platform that integrates data collected from aircraft, for example, a firm such as Boeing would not be able to provide most of its services today (Box 2.4). The company would be unable to compete with large players in its industry sector, such as Airbus, which in fact is making a similar effort, expanding its ability to monitor its aircraft, including the A 380-1000 (Marr, 2015).

Within many organisations, silos still exist today, preventing the sharing of data and thereby creating frictions (cross-organisational) in value chains. According to a survey by The Economist Intelligence Unit (2012), for example, almost 60% of companies consider that organisational silos are the biggest impediment to using big data for effective decision making. Executives in firms with annual revenues exceeding USD 10 billion are more

likely to cite data silos as a problem (72%) than those in firms with revenues below USD 500 million (43%).

Box 2.4. **System integration via the cloud: The case of Boeing**

Aircraft manufacturers such as Boeing and Airbus face a challenge today as modern commercial aircraft are becoming smart "flying boxes of electronics". These companies need to be able to evaluate and manage systems on-board their aircraft as well as manage electronic controls and monitor physical features, such as wing flaps, in real time. In addition, the manufacturers need to provide support and maintenance information to the airlines that fly their aircraft, making them simple to repair and minimising time on the ground. To respond to these challenges, aircraft manufacturers integrate their own historical data – data on aircraft performance and maintenance – with data generated by aircraft and product information from suppliers. To do this, integrated databases are needed to support a wide range of services such as: delivering parts as they are needed (material services); optimising fleet performance and operations (how entire fleets of different airlines' planes are managed and operated);[1] giving access to flight services based upon real-time, in-flight data; and supporting information services that provide insights into managing any of these services.

Boeing is beginning to provide products that combine a physical good (an aircraft) and digital (data-driven) services. The move to add a series of new services to its product is related to a broader objective to build a capability to manage and control its production and service systems. There are three changes that characterise Boeing's recent efforts. First, Boeing has employed a combination of big-data analytics and the IoT to manage and evaluate its supplier network.[2] Second, Boeing has deployed a system of interconnected robots and intelligent software on the factory floor (see Boeing [2013a] and Airbus Group [2016]). This complex, interconnected system requires new management skills and also serves as a link to Boeing's suppliers' information systems. Third, Boeing has developed software to manage and analyse the many on-board aircraft systems.

By making these changes, Boeing is able to do almost real-time analysis of sensor information that it receives from planes that are in the air. These analyses support the development of new services for its customers. This is part of Boeing's move to expand the company's focus from aircraft to customer services. In its latest model, the Boeing 787, "146 000 data points are continually monitored by on-board systems and automatically transmitted to the ground" (Boeing, 2013b).

The three changes highlighted above required a digital infrastructure to support the exchange and analysis of data. To achieve this, the firm created a service "platform" named Boeing Edge, through which airlines that use Boeing's planes can access information about the services described above.

In addition, Boeing has put in place a cloud-based computer system, the Digital Aviation Platform, a PaaS that allows application developers to build software from components that are hosted on the platform. The interconnection between airlines' back office systems and the Digital Aviation Platform is enabled by APIs. Such back office systems include schedules, billing or settlements, clearances, record maintenance, regulatory compliance, accounting and information technology (IT) services. They typically manage information on aircraft maintenance, passengers, and flights (Crabbe, 2013).

Boeing has also created a database-as-a-service infrastructure that relies upon Amazon Web Services. This contains over 20 000 databases that describe the parts used throughout planes as well as the instructions for replacing them. These databases are accessible to airlines through a secure connection.

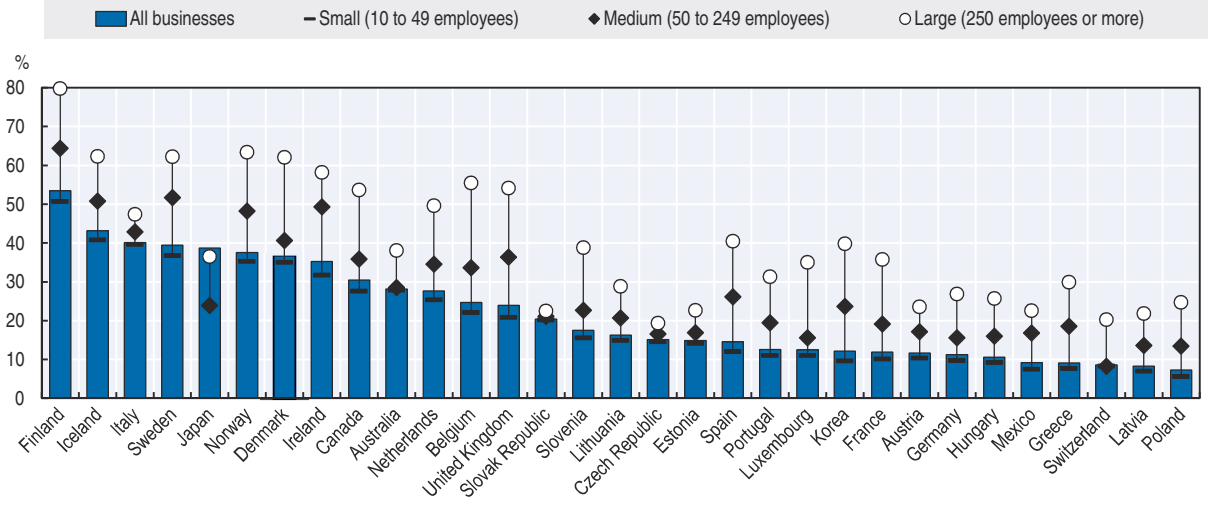
Box 2.4. **System integration via the cloud: The case of Boeing** *(cont.)*

Boeing is also building a Center for Applied Simulation and Analytics (CASA), to create and develop simulation and analytics technologies to evaluate the designs and likely performance of both newly conceived and already operating aircraft.

An effect of the enhanced capacity of Boeing to manage and control its systems is its greater power over its suppliers. In 2015, for example, Boeing influenced mergers of suppliers "by using its power to approve the transfer of its supply contracts from one owner to another … Because of such 'assignability clauses' that give Boeing the right to deny the transfer of existing contracts to a new firm", Boeing can "refuse to transfer the contracts to the new owners, giving it a de facto veto over deals" (Scott, 2015). As data on suppliers' parts is incorporated into Boeing's data analytics systems, Boeing can now exercise even greater influence over its engine and parts supplier base as the use of data analytics gives Boeing greater knowledge of its suppliers' operations. With this greater information asymmetry comes a significant shift in power away from the suppliers in favour of Boeing.

1. While this was previously largely a priority for airlines, Boeing's access to a wide range of information about aircraft performance and management via the IoT has given it a significant role in interpreting real-time data and aircraft performance. This changes its economic role with respect to the airline industry.
2. Boeing implemented a more sophisticated supply chain for its 787 model, but because of problems with suppliers lost billions of dollars in work on the innovative aeroplane (see Denning, 2013).

Figure 2.4. **Percentage of enterprises in each employment size class using cloud computing services in 2014**



Notes: Data for Belgium, Denmark, Finland, Greece, Hungary, Ireland, Latvia, Lithuania, Norway, Poland, Slovak Republic, Slovenia, and Spain refer to 2014. Data for Canada and Mexico refer to 2012. Data for Canada only include the use of SaaS, a subcategory of cloud computing services.

Source: Based on OECD (2017b), *OECD.Stat*, database, *http://dotstat.oecd.org/index.aspx?DatasetCode=ICT_BUS* (accessed March 2017).

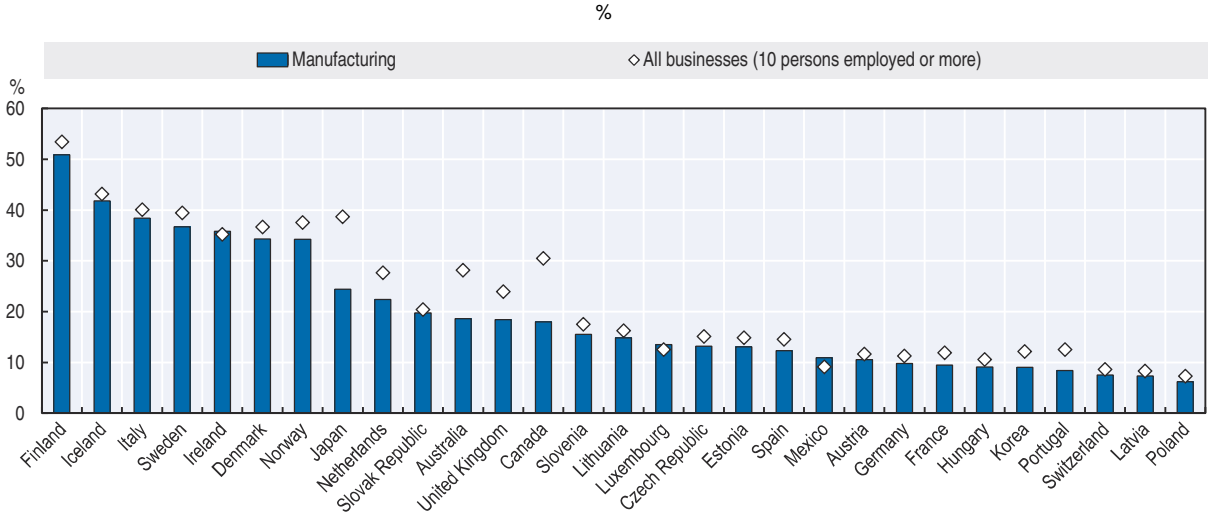
StatLink http://dx.doi.org/10.1787/888933473755

Cloud computing can help to overcome these silos and make organisations more cohesive and automated by enabling data to be stored and accessed from a common data repository in the "cloud" (Rüssmann et al., 2015). This requires the interoperability of cloud computing-enabled services, for example, through accessible application programming interfaces (APIs). However, the lack of appropriate standards and vendor lock-in due to proprietary solutions can be a barrier to the interoperability of these services. This makes

the lack of appropriate standards and vendor lock-in the most frequently highlighted barriers to cloud computing adoption besides privacy and security concerns (OECD, 2015a, Chapter 3).

However, significant variation still exists across countries and firm size in its adoption. In countries such as Finland, Israel, Italy, Sweden and Denmark, almost half of all businesses already use cloud computing services, although this percentage is much lower in most other countries (Figure 2.4). There is also large variation in use by business size, with larger enterprises (250 or more employees) more likely to use cloud computing. In the United Kingdom, for example, 21% of all smaller enterprises (10 to 49 employees) use cloud computing services, compared to 54% of larger enterprises. In some countries there is also a notable difference in adoption of the cloud in manufacturing and its adoption in the rest of the economy (Figure 2.5).

Figure 2.5. **Share of manufacturing firms using cloud computing services by country, 2015**



Notes: Data for Australia, Austria, the Czech Republic, Estonia, France, Germany, Iceland, Italy, Luxembourg, the Netherlands, Portugal, Sweden, and the United Kingdom refer to 2014. Data for Korea refer to 2013. Data for Canada, Japan, and Mexico refer to 2012. Data for Switzerland refer to 2011. Data for Canada refer to the use of SaaS, a subcategory of cloud computing services.
Source: OECD (2016f), *OECD.Stat*, database, *http://dotstat.oecd.org/index.aspx?DatasetCode=ICT_BUS* (accessed September 2016).
StatLink http://dx.doi.org/10.1787/888933473767

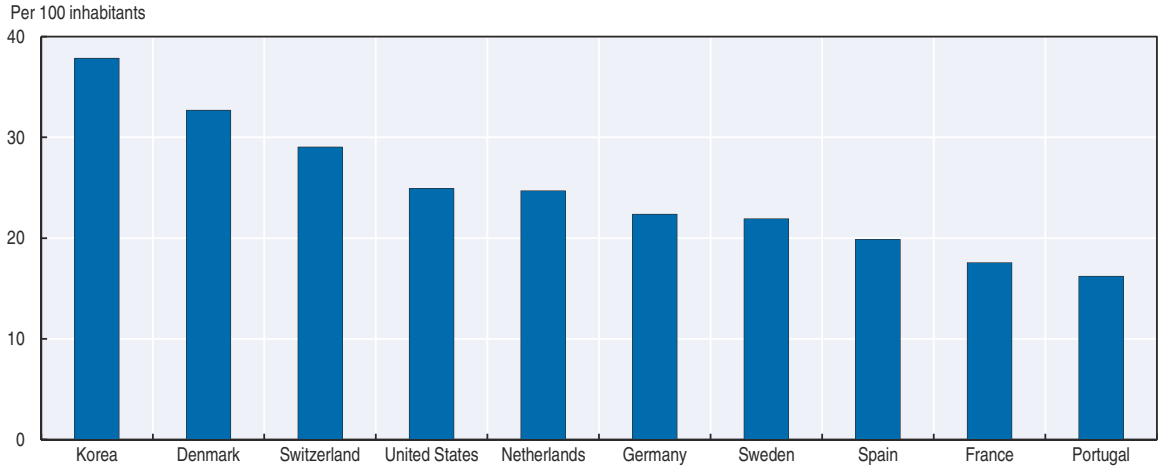
The IoT is a game changer

The IoT is a term referring to the connection of devices and objects to the Internet's network of (public and private) networks. Among the interconnected objects, the IoT also includes sensors and actuators, which in combination with big-data analysis and cloud computing enable autonomous machines and intelligent systems.

Measurement of the number of IoT devices connected to the Internet has proven hard to obtain, with countries only now starting to collect data. But one source (Shodan, the world's first search engine for Internet-connected devices) finds 363 million devices online with some 84 million registered to the People's Republic of China (hereafter "China") and 78 million to the United States. Korea, Brazil and Germany follow with 18 million connected devices, and Japan, Spain, the United Kingdom and Mexico make up the rest of the top ten countries, with 8 million to 10 million devices each. Efforts to rank devices per capita are hindered by data limitations, but the top ten is shown in Figure 2.6.

Figure 2.6. **IoT devices online, top OECD countries**

Per 100 inhabitants



Source: OECD (2015a), *OECD Digital Economy Outlook 2015*, *http://dx.doi.org/10.1787/888933225312*, based on Shodan, *www.shodanhq.com*.

StatLink http://dx.doi.org/10.1787/888933473770

Available estimates suggest that the IoT could contribute USD 10 trillion to USD 15 trillion to global GDP over the next 20 years (Evans and Anninziata, 2012). Equipping machines with sensors could allow efficiency-enhancing predictive maintenance. A 1% efficiency increase in the aviation industry could, for example, save commercial airlines globally USD 2 billion per year (Evans and Anninziata, 2012). According to Vodafone (2015), adopting the IoT brings average cost savings for industry of 18%, and nearly 10% of IoT adopters have reduced their costs by over 25%. Apart from cost savings, companies cite other areas of identified improvement, including: process efficiency; customer service, speed and agility of decision making; consistency of delivery across markets; transparency/predictability of costs; and performance in new markets (Vodafone, 2015). For example, the use of big-data analytics in combination with the IoT, has enabled a major US automaker to save about USD 2 billion over the last four to five years (Box 2.5). These economies mainly come from optimising supply chains. In addition, the company uses simulations based on big data to optimise truck design so that fuel efficiency is improved and production costs are reduced.[9] The IoT will also give rise to many economic and social benefits not directly related to production, e.g. in health, in the use of smart meters and in the efficiency of vehicle usage.[10]

Box 2.5. **The IoT, big data, and cloud computing used by a major US automaker**

A US automaker has saved around USD 2 billion in costs over the past five years (2011-14 and most of 2015) by developing a significant IoT and data analytics capability. It did this to provide insights into its vehicles' designs, estimating e.g. by how much using aluminium would improve fuel efficiency before a new truck design was put into production. The largest savings were from changes in the automaker's supply chain and increased efficiency in dealerships.

There are two main areas where this automaker has achieved substantial benefits. First, controlling its supply chain better. Second, using data analytics to improve the selection of vehicles, colours and features that dealers will offer to customers.

Box 2.5. **The IoT, big data, and cloud computing used by a major US automaker** *(cont.)*

For its supply chain, it is assumed that parts constitute about one-third to one-half of the value of a vehicle costing USD 30 000. It is also assumed that the firm can reduce costs in its supply chain by about 1% to 1.5% a year by using data analytics (based upon studies of other firms). This assumes that the firm sells USD 20 billion worth of vehicles in the United States annually. This would result in a savings of USD 200 million to USD 300 million a year, or USD 1 billion to USD 1.5 billion over five years. In terms of improving the selection of cars sent to dealers, one measurable gain would come from optimising inventories by reducing the time cars spend on dealer lots. This might represent around USD 50 to USD 100 per car for about 2 million cars a year, or USD 500 million to USD 1 billion over five years. Overall these savings would lead to a total saving of USD 1.5 billion to up to USD 2.5 billion in cost savings over five years.

The investments required to achieve these cost savings were estimated to be between USD 350 million and USD 500 million over five years. It is assumed that this major US automaker used 200 employees in the digital analytics group and that these people were paid about USD 150 000 to USD 200 000 per year on average (this estimate is on the high side because some specialists have incomes of more than USD 300 000 or more a year) with all expenses rolled in. This would sum to a USD 30 million to USD 40 million annual cost, or about USD 150 million to USD 200 million over five years. If it is further assumed that the costs of the software and hardware for data analytics are about the same magnitude or possibly slightly larger, the cost of setting up the automaker's software-defined architecture to support data analytics and create an (internal) IoT would be about USD 200 million to USD 300 million over five years. Overall, this would represent roughly a USD 2 billion return on an investment (ROI) of USD 350 million to USD 500 million over five years, or a ROI of 300% to 470%.

Estimates of how the firm's move into the IoT is likely to impact its financial performance show that the biggest area for savings is likely to come from the firm's efforts to control costs in its supply chain. The firm has already consolidated production on a single platform to reduce the number of parts it needs in a car. With a more sophisticated analytic system, it should be able to achieve additional savings. The automaker is also studying how to link more vehicles with on-board sensor platforms to its cloud. It is experimenting with sensors to help drivers improve their performance. For electronic cars, there is already an Internet-based system that ties into mobile devices. This tells a driver whether the car's battery is charged. The system can also identify nearby charging locations. The firm has not estimated the size of this benefit, nor has it forecast how much it might expand if there is a larger fleet of electrically powered cars in the future.

Currently, the firm's electric vehicles generate about 25 petabytes[1] of data an hour. So the firm expects there will be about 100 times more data than this per car from new satellite technologies which could be introduced over the next two to three years. In addition, the firm's sensors in plants, on factory floors and in research programmes generate a lot of data. The automaker sees the vehicle as a "closed-loop control system". This might result in the firm receiving exabytes[2] of additional data from new systems in tens of millions of vehicles, or zettabytes of data per year by 2019-20. This would be a remarkable rate of growth of over 250% per year, and would raise some big challenges in terms of data management.

1. 1 petabyte = 1 million gigabytes.
2. 1 exabyte = billion gigabytes.

The IoT, together with big data and cloud computing, are the main reasons for the sudden breakthrough in artificial intelligence (AI) applications, like driverless cars. The IoT embeds physical objects in information flows and thereby makes them "smarter". With driverless cars, for example, the road infrastructure, other cars, and web services (such as online maps) tell a car what it needs to know.[11] In this way, it is not necessary to equip a car with image processing systems comparable to human vision for the car to be able to drive on its own, as was previously assumed. Similarly, when all the devices and machines in a factory can supply information, many new robotics applications become possible.

The digital transformation of production is highly disruptive

The use of digital technology often induces the "creative destruction" of established businesses, markets and value networks. This can be particularly challenging for (traditional) businesses, where the competitive environment may discourage investments in disruptive innovation in the short run. This is often the case for two reasons: first, investments in disruptive innovation can take scarce resources away from sustaining the most profitable business units (which are needed to compete against current competition); and second, disruptive innovation is often highly risky given that it may not be profitable in the short run. Disruptive innovation may require substantial changes in organisational structures, business processes or even business models that involve sunk costs (that cannot be recovered).[12] In addition to economic factors, these changes may also be hard to implement in light of internal resistance due to the organisational culture and psychological resistance among management and their employees. Christensen (1997) refers to this challenge as the innovator's dilemma, where successful companies put too much emphasis on current success, and thus fail to innovate in the long run.

The fear of change and disruption combined with short-term thinking in traditional established businesses means that digital innovation is introduced more frequently by ICT firms, and in particular start-ups (see OECD [2015b]). As shown by Criscuolo, Nicolaou and Salter (2012), new technologies and innovations are often first commercialised through start-up companies because they can leverage the advantage of starting without the legacy of an existing business and customer base and thus can create a variety of presumably new business models. Christensen (1997) also argues, controversially, that disruptive innovations are often not valued by existing customers at first. As a consequence, incumbents, which tend to be most responsive to their main customer base, may ignore the markets most susceptible to disruptive innovation, even if they invest heavily in research.

For traditional businesses this means that they will face a more complex competitive landscape where they will "be forced to compete simultaneously on multiple fronts and co-operate with competitors" (Gao et al., 2016).[13] The competitors may include ICT firms such as Alphabet (Google) and Apple, which have competitive advantages in digital technologies. The creation of new business models which could disrupt established industries may be necessary. As a consequence, traditional businesses may have to rethink their business models to stay competitive in the long run.

New business models are characterised by an emphasis on high value-added services

As goods become commodities with low profit margins, many manufacturing firms are developing new complementary services that extend their current business propositions. Rolls-Royce, for example, shifted its business from a product, time and service solution to a service model trademarked as "Power by the Hour" (PBH) (Box 2.6). Digitalisation has been a key enabler for this transformation towards higher value-added (complementary) services.

Box 2.6. **The "servicification" of manufacturing: The case of Rolls-Royce's "Power by the Hour" (PBH)**

Rolls-Royce shifted its business from a product, time and service solution to a service model trademarked as "Power by the Hour" (PBH).[1] With PBH, customers pay only for the time they use an engine. Rolls-Royce could do this only by being able to collect large amounts of data from the sensor networks it installed on engines.

Rolls-Royce's service model evolved through three steps. First, it developed ways to use the data from sensor networks to manage its own service operations. Second, it enhanced the model by more directly managing the services and support for clients. Third, it was able to make large amounts of data more generic across many different customers, optimising its entire data ecosystem. This has enabled Rolls-Royce's service model to become proactive, with the aim of minimising, or eliminating, disruptions caused to its customers (Frank-Partners YouTube channel, July 2016).

This new business model changed from product and sales support to a services business. It insured that Rolls-Royce captured its aftermarket service business rather than permitting third parties to create parts to service its aircraft engines. The new business model also meant that the risks of using an engine were more equitably distributed between the supplier and the customer.

Rolls-Royce started this approach by integrating its customers very closely within its own operations. It began by working closely with American Airlines to create the Total Care solution focusing on the customer's end-to-end needs. This led to the creation of Operations Centres where Rolls-Royce's engineers oversee the day-to-day management of a customer's fleet. In many cases, these centres are embedded within a customer's operations, beginning with closely linked operations in the defence industry in the United Kingdom (Frank-Partners YouTube channel, July 2016).

Rolls-Royce now focuses on "zero-based disruption" for its customers. To achieve this, Rolls-Royce does sophisticated modelling of the solutions it offers customers. It does this on a product basis as well as for customer fleets. This shift of focus to prognostics means actively taking data off engines and aggregating the data to understand how the entire fleet works. Rolls-Royce can then aggregate the data across customers to gain an overview of how data is used. In the future, Rolls-Royce will also focus on dispatch availability, ensuring that when an aircraft rolls onto a runway, it has the highest chance of taking off without problems originating from its engines.

Rolls-Royce's new service model provides two ways of improving the firm's performance:

- **Rolls-Royce can reduce the costs of scheduled repairs by cutting maintenance costs and preventing breakdowns, thereby lengthening the time that an engine can stay on the wing. This increases its service revenues.** One of the US national laboratories has estimated that "Predictive maintenance of assets [can save] up to 12 % over scheduled repairs, reducing overall maintenance costs up to 30 % and eliminating breakdowns up to 70 %." (Sullivan et al. [2010]; cited in Daugherty et al. [2015]). If Rolls-Royce's savings are on this scale, based upon fiscal year 2014 revenues, it could be saving 12% on its cost to provide services. These cost savings might range from USD 400 million to USD 600 million. Rolls-Royce not only extends the expected lifetime of an engine, it also collects additional income from the services to support an engine. It does this by extending the life of an engine from the usual four to six years to six to eight years. This would permit Rolls-Royce to increase revenues on services for both its civilian and defence aerospace operations. This could mean increasing earnings of service revenues by 15% to 20 % per year.

Box 2.6. **The "servicification" of manufacturing: The case of Rolls-Royce's "Power by the Hour" (PBH)** *(cont.)*

Based on fiscal year 2014 revenues, this would be an additional USD 1.0 billion to USD 1.35 billion annually. So, the total annual benefit from the new service model could be more than USD 1.4 billion to USD 1.95 billion.

- **Rolls-Royce can provide a form of service assurance to its customers when it provides dispatch availability and "zero-based disruption":** By reducing disruptions to its customers' ability to operate, Rolls-Royce is adding performance assurance to the usual services it offers through its Operations Centres and Business Centres. However, it is difficult to estimate this type of economic impact stemming from zero-based disruption.[2]

1. With Power by the Hour, "Customers and suppliers of mission-critical products, such as semiconductor manufacturing equipment, commercial aircraft and military weapon systems, are recognising that the acquisition of world-class products is not sufficient, but rather it is necessary to provide superior, cost-effective maintenance and support services throughout the after-sales phase of the customer-supplier relationship. A major focus of these efforts involves re-designing the contractual and implicit relationships between customers and suppliers in the service support supply chain." (Knowledge@Wharton, 2007).
2. Information on the economic value of "zero-based disruption" is not available. A case study of FANUC's zero downtime efforts suggests that it might reduce General Motor's downtime and save General Motors USD 40 million per year (see Roboglobal, [2016] and Cisco [2016]).

Historically, the digital transformation of business models was first enabled by the formalisation and codification of business-related activities, which led to the computerisation of business processes via software. This has "enabled firms to more rapidly replicate improved business processes throughout an organisation, thereby not only increasing productivity but also market share and market value". Brynjolfsson et al. (2008) have referred to this phenomenon as scaling without mass. Internet firms pushed the digital transformation to a new level. This enabled them to better scale without mass, when compared to the rest of the economy.[14]

The business models of the most successful Internet firms today go beyond the formalisation and codification of processes via software, and now involve the collection and analysis of large streams of data (OECD, 2015b). By collecting and analysing big data, a large share of which is provided by Internet users (consumers), Internet companies are able to automate their processes and to experiment with, and foster, new products and business models at a much faster rate than the rest of industry. Instead of relying on the (explicit) formulation and codification of business processes, these firms use big data to "train" AI algorithms to perform more complex business processes without human intervention. Innovation enabled by AI is now used to transform business processes across the economy. Thanks to the convergence of ICTs with other technologies (owing in particular to embedded software and the IoT), the digital transformation has the potential to affect even traditional sectors such as manufacturing and agriculture.

The analysis of successful digital business models suggests that actions that take advantage of the applications mentioned above can digitally transform traditional businesses. These actions include:

- **The digitisation of physical assets**, which refers to the process of encoding information into binary digits (i.e. bits) so that it can be processed by computers (OECD, 2015b). This is one of the most straightforward steps to digitally transform businesses. An early example is the entertainment and content industry, where books, music, and videos were digitised to be provided over the Internet. Thanks to the deployment of 3D scanners

and 3D printing, digitisation is no more limited to content, but can now include real-life objects. 3D printing promises, for example, to shorten industrial design processes, owing to rapid prototyping, and in some cases raise productivity by reducing material waste (see Chapter 5). Boeing, for example, has already replaced machining with 3D printing for over 20 000 units of 300 distinct parts (Davidson, 2012).

- **The "datafication" of business-relevant processes,** which refers to data generation, not only through the digitisation of content, but through the monitoring of activities, including real-world (offline) activities and phenomena through sensors. "Datafication" is a portmanteau term for "data" and "quantification" and should not be confused with "digitisation", which is just the conversion of analogue source material into a numerical format (OECD, 2015b).[15] Datafication is used by many platforms which monitor the activities of their users. And with the IoT, this approach is no longer limited to Internet firms. For example, data collected on agricultural machines, such as those made by Monsanto, John Deere and DuPont Pioneer, are being used as an important data source for optimising the distribution and genetic modification of crops (GMC) (Boxes 2.3 and 2.6).
- **The interconnection of physical objects via the IoT** enables product and process innovation. Scania AB, a major Swedish manufacturer of commercial vehicles, now generates one-sixth of its revenues through new services enabled by the wireless communication built into its vehicles (Box 2.7). This allows the company to transition towards a firm increasingly specialised in logistics, repair and other services. For example, with the interconnection of its vehicles, Scania can better offer fleet management services. The interconnection of physical objects also enables the generation and analysis of big data, which can be used for the creation of more services: for example, Scania offers a set of services to increase driving (and therefore resource) efficiency, such as data-based driver coaches.
- **The codification and automation of business-relevant processes via software and AI.** software has enabled and incentivised businesses to standardise their processes, and where processes are not central to the business model, to sell the codified processes via software to other businesses. An example is IBM's Global Expenses Reporting Solutions, which were originally developed to automate the company's internal travel-related reporting. IBM turned the in-house system into a service, which it has sold globally (Parmar et al., 2014). Another example is Google's Gmail. This was originally an in-house e-mail system, before it was announced to the public as a limited beta release in April 2004 (McCracken, 2014).

Box 2.7. **Co-operation or competition: The case of Scania's Connected Vehicles**

Scania AB, a major Swedish manufacturer of commercial vehicles, is increasingly using its so-called "communicator" to collect data to monitor and analyse the efficiency of its vehicles. Scania aims to increase the share of its services sales to 25% to 30% of total sales by 2020. Scania's services have traditionally comprised technical and financial services, but are increasingly shifting towards various connected services. The company intends around one-sixth of its sales in the product service area to be connected services by 2020.

There are several reasons why Scania has chosen to put more emphasis on services. Since service sales are not affected by economic fluctuations in the same way as sales of newly produced vehicles, the company has an ambition to create a better balance in the company's sales over the business cycle. Scania also sees conversion to services as a way

Box 2.7. **Co-operation or competition: The case of Scania's Connected Vehicles** *(cont.)*

of increasing sales by creating new services that meet changing customer demands in the transport sector. The combination of services and vehicles also makes it possible for Scania to more clearly create its own niche in the market for heavy vehicles. In this area, Scania wants to strive for its connected vehicles to work smoothly in transport companies with fleets containing vehicles from different manufacturers.

According to Scania, the industry trend is towards transport companies specialising in logistics, but outsourcing repairs and other services. The relationships between Scania and its customers are also shifting to more of a partnership, where the parties jointly work to develop and optimise the profitability of vehicles and thus to improve the customers' profitability. To do this, it is important for product development towards more sustainable, safe and efficient vehicles to take place in co-operation with customers. Using various (digital) services, Scania aims to influence both the customers' costs and revenues. On the cost side, this may involve more efficient fuel consumption or service programmes. On the revenue side, the primary profitability factor is the actual time the vehicle is available for transport work.

The developments towards connected vehicles create a need for access to new cutting-edge expertise and capacities. This means that vehicle manufacturers such as Scania need to enter new kinds of partnerships with ICT companies. At the same time, this development also opens up new competition from ICT and other kinds of companies that see opportunities to take over parts of the value chain in the transport industry. Furthermore, other stakeholders, such as insurance companies and suppliers of automobile components, also see new business opportunities, for example from having better access to vehicles' sensor data.

For automotive industry firms such as Scania, a crucial issue is therefore where in the mobility value chain the major value will be generated in the future and how today's technical developments affect this. Scania has chosen to move towards greater delivery of services that meet changing customer needs in transportation. At the same time, market developments have made it more difficult for Scania to take payment for certain services that were previously a strategic part of its product portfolio. One example is the support for the management of a transport company's vehicle fleet, so-called "fleet management services". Over time, fleet management services have been standardised, and today there are many third-party suppliers that put pressure on prices.

Finally, Scania also faces a number of challenges that are directly affected by public policies. For example, the company increasingly relies on an excellent mobile network infrastructure. Given that Scania does not own communication networks, it must instead join roaming partnerships with global telecommunication operators to guarantee that its digital services work.

Last, but not least, the transition towards driverless vehicles, which Scania foresees occurring in the next 5 to 25 years, raises new challenges related to issues of liability tied to traffic safety that are difficult to anticipate legally.

- **The trading of data** (**as a service**) is made possible as soon as physical assets have been digitised or processes "datafied" (see bullet above on "datafication"). Data generated as a by-product of doing business can have huge value for other businesses (including in other sectors). The French mobile communication services firm, Orange, uses its Floating Mobile Data (FMD) technology to collect mobile telephone traffic data that are

anonymised and sold to third parties, including government agencies and traffic information service providers. In addition, businesses can take advantage of the non-rivalrous nature of data to create multi-sided markets, where activities on one side of the market go hand in hand with the collection of data, which is exploited and used on the other side of the market. Very often, however, it will be difficult to anticipate the value that data will bring to third parties. This has encouraged some businesses to move more towards open data (see OECD, 2015b).

- **The (re-)use and linkage of data within and across industries** (i.e. data mashups) has become a business opportunity for firms that play a central role in their supply chain. Walmart and Dell have successfully integrated data across their supply chains. But as manufacturing becomes smarter, thanks to the IoT and data analytics, this approach is becoming attractive to manufacturing companies as well. Sensor data, for example, can be used to monitor and analyse the efficiency of products, to optimise operations at a system-wide level, and for after-sale services, including preventative maintenance operations (see the example of Schmitz Cargobull discussed earlier).

The competitive landscape is becoming more complex with co-opetition becoming the new default

The increasing importance of ICTs such as big-data analytics, the IoT, and AI gives companies that can take advantage of these technologies a significant competitive advantage. ICT firms able to extend the scope of their businesses to other sectors can have an advantageous starting position. For established (traditional) businesses, however, the situation is challenging: they not only need to better understand how to best use ICTs, they also have to forge new partnerships with ICT firms to gain the necessary technical capabilities.

Some traditional businesses have decided to acquire promising ICT start-ups (for example John Deere acquiring Precision Planting), while others have started to co-operate with ICT firms, which however, could rapidly become competitors (Box 2.7). This slightly ambiguous relationship between co-operation and competition has been referred to in the literature as "co-opetition".

The complexity of the competitive landscape can be observed in the automobile industry, where traditional automotive firms not only compete with their direct competitors, including new entrants such as Tesla, but increasingly compete with ICT firms such as Apple, Alphabet (Google) and Uber Technologies (Uber), to name a few. This profound change in the competitive landscape is driven by a number of social and technological trends. Among these trends, the following three are seen as the most important in the automobile sector:

- **The increasing degree to which ICTs, in particular software, are embedded in vehicles.** The cost of developing new vehicles is increasingly dominated by software, with high-end vehicles relying on millions of lines of computer code. It is estimated that 90% of the new features in cars have a significant software component (e.g. improved fuel injection, on-board cameras and safety systems). Hybrid and electric vehicles in particular require huge volumes of computer code: the Chevrolet Volt plug-in hybrid uses about 10 million lines of computer code. A major part of the development costs for entirely new vehicles is also software-related (while manufacturers guard the exact figures closely, estimates of around 40% are not uncommon) (OECD, 2015d).

- **The trend towards autonomous (self-driving) vehicles, which means that software systems using AI will account for most of the value-added in an automobile.** Software would constitute the major part of the development costs (rising to between 60% and 80% when including infotainment systems[16]). It is therefore not surprising that firms with strong software capabilities, in particular in AI, have entered the field of self-driving cars. Google is often perceived as one of the pioneers, as it started its Self-Driving Car Project in 2009 (although many of the leading automobile companies have been working on the concept for at least a decade[17]). Tesla's recent firmware update enabling its semi-autonomous "Autopilot" system has also put significant pressure on incumbents in the automobile market to accelerate the release of products with comparable features (see for example, Toyota Motor announcing it will invest USD 1 billion through to 2020 to develop self-driving cars).
- **A possible paradigm shift towards "mobility as a service" which may make car ownership less attractive.** Mobile smartphones and applications (apps), combined with the analysis of big data, have enabled collective consumption of private durable goods by providing access to excess capacity of these goods. In the case of cars, many shared mobility services have emerged, ranging from the rental of private cars (Zipcar), rides (Uber, Lyft, BlaBlaCar) and parking spaces (JustPark), to the rental of free floating (Car2go, DriveNow) and station-based cars (Autolib') and bikes (Vélib') (OECD, 2015a). A great deal of capital is therefore flowing to these firms. For example, Apple has recently invested USD 1 billion in Didi Chuxing, a ride-hailing service competing with Uber in China.

All these trends have favoured the market entry of ICT firms in the automobile and mobility services sector, increasingly through strategic alliances, but also mergers and acquisitions (M&As). A number of these alliances have focused on the development of autonomous (self-driving) vehicles. For example, in May 2016 Fiat Chrysler Automobiles and Alphabet, Google's mother company, announced that they would jointly develop a fleet of 100 self-driving minivans. The following month, BMW announced that it would team up with Intel and Mobileye to develop a fully automated driving system. In terms of M&As, General Motors recently paid USD 1 billion for the acquisition of Cruise Automation, a start-up specialised in the development of hands-free driving software systems.

There have also been an increasing number of collaborations and investments focusing on mobility as a service. For example, Volkswagen recently invested USD 300 million in an Israeli start-up, Gett, an Uber rival operating mainly in New York, London, Moscow and Tel Aviv. Similarly, Toyota Motor Corporation invested in Uber Technologies, while General Motors invested in USD 500 million in Lyft, Uber's top US rival, which has plans to develop a nationwide on-demand network of self-driving cars. For the platform providers the objective is often to gain access to fleets of cars, while the car manufacturing companies are interested in gaining access to the mobility data and analytic capabilities of the platform providers.

In light of these collaborative efforts, some observers have noted that automobile manufacturers may be pushed towards the lower end of the value chain if they lack competencies in software and AI-enabled services. For example, when commenting on Apple's announcement to invest in a car project, Ewing (2015) concluded that:

"The main risk for car makers is probably not so much that an Apple car would destroy Mercedes-Benz or BMW the way the iPhone gutted Nokia, the Finnish company that was once the world's largest maker of mobile phones. Rather, the risk is that Apple and Google would turn the carmakers into mere hardware makers – and hog the profit."

That said, the traditional carmakers' big advantage is still their capacity to manage the complexity of manufacturing reliable, comfortable vehicles including the management of the supply chain. And these companies still possess very strong brands. To what extent a newcomer will be able to outsource the manufacturing process, like Apple outsources the production of the hardware for the iPhone, or to partner with manufacturing firms, as Google does with Android, is hard to tell. In any case, it will be crucial for all stakeholders to clearly identify their core business areas and the activities in the value chain where they can best lever their competitive advantages. The exploitation of existing intellectual property rights (IPR) and data as "points of control" could turn out to be key to firms' strategies, with important implications for competition in these markets to be expected (see OECD [2015b]).

The automation of manufacturing and agriculture

In manufacturing, robots have traditionally been used mostly where their speed, precision, dexterity and ability to work in hazardous conditions are valued. Traditional robots, however, could only operate rapidly in very precisely defined environments. Setting up a robotic plant would take months, if not years. The robots might have sensors on-board but most of their movements would have to be pre-planned and programmed, which would not allow for much flexibility in production. For this reason, the production of consumer electronics is still often done by hand, because the life cycle of consumer electronics and the time to market is so short that a robotic factory would not be ready to make the current product by the time the successor should be on the market. However, this is radically changing because AI machines are becoming more flexible and autonomous and can now perform a wider range of more complex manual work. Some modern factories, such as the Philips shaver factory in Drachten in the Netherlands, are almost fully robotic (Markoff, 2012). This particular factory employs only one-tenth of the workforce employed in Philips' factory in China that makes the same shavers.

In agriculture, autonomous machines are increasingly used. In cattle farming, for example, machines milk cows, distribute food and clean stables without any human intervention. The milking robot from Lely, for example, autonomously adjusts the feeding and milking process to optimise milk production for each cow. Some studies have therefore suggested that it is only a matter of time before humans are removed altogether from agricultural farming.

A scenario might ensue in which farm enterprises become local caretakers of land, animals and data. They might monitor operations that are centred at the lower end of the value chain, much like the current concept of contract farming.[18] Food producers, retailers or even end consumers could interact directly with the network around the farmer, including seed suppliers, smart (autonomous) machines, veterinarians, etc. In such a scenario, the job of the farmer would be more like a contractor making sure that the interactions between the supply and demand sides of the agricultural system work together properly. In an alternative scenario, farmers could become empowered by the data and intelligence provided by analytics, tailoring the processes to their knowledge of local and farm-specific idiosyncrasies.

As the IoT enables integration of physical systems, it will also foster the integration of living systems – including plants, animals and humans – within physical systems.[19] Such integration may further empower humans: augmented reality-based applications, for example, could provide workers with the real-time information to improve decision making and work procedures. For example repair instructions could be displayed directly in workers' field of sight using augmented reality glasses (Rüssmann et al., 2015). And by using

information available in real time, employees could organise shift scheduling themselves, as the case of KapaflexCy in Germany shows (Box 2.8). That said, examples presented so far suggest that there are also risks that such integration may lead to a dehumanisation of production. In highly automated production processes, integration and interaction between humans and autonomous systems have already emerged in particular for tasks for which human intelligence is still required and no cost-efficient algorithm exists, making human workers appear rather as servants than users of IoT-enabled systems (Box 2.9).

Box 2.8. **Self-organised capacity flexibility for Industry 4.0: The KapaflexCy research project**

To produce highly customised products, companies must become more dynamic, agile and customer-oriented. This requires maximum flexibility, from technical facilities and personnel. For lean production, the deployment of personnel must be matched as closely as possible to real-world demand. In practice, this process is usually inefficient: team leaders and shift managers co-ordinate the presence and absence of employees, usually verbally, and sometimes by e-mail.

In the KapaflexCy research project, a number of institutions working together developed a self-organised capacity control system (the institutions concerned were Fraunhofer IAO, together with BorgWarner, Bruker Optik, Stuttgart Airport, the Institute for Occupational Safety and Technology Management, Introbest, Kaba, SAP and Trebing and Himstedt). This system allows companies to control their production capacities with the direct involvement of executive employees in a highly flexible, short-term and company-wide manner. Even with fluctuating orders and unstable markets, companies can react more quickly, avoid unproductive times and reduce the cost of capacity control. Employees experience a transparent personnel deployment plan and co-ordinate their deployment times. The balance between work, family and leisure has been improved, and motivation increased.

Source: OECD, based on *www.plattform-i40.de/I40/Redaktion/DE/Anwendungsbeispiele/096-kapaflexcy-selbstorganisierte-kapazitaetsflexibilitaet-fuer-die-industrie-4-0/beitrag-kapaflexcy-selbstorganisierte-kapazitaetsflexibilitaet-fuer-die-industrie-4-0.html* (accessed 15 January 2017).

Box 2.9. **Crowdsourcing of human intelligence tasks: "Human computing"**

While computing and automation technologies are steadily improving, humans still do many tasks more effectively than computers, such as identifying objects in a video, and transcribing audio recordings. For such tasks, firms have tended to hire temporary workers. But crowdsourcing a workforce for human intelligence tasks (HITs) is an increasingly used alternative. This process, which gives firms flexibility, is often referred to as "human computing", because humans are here used solve problems that computers cannot.

Amazon is still the most prominent provider of human computing services over the Internet, since it launched its crowdsourcing marketplace for digital work called Amazon Mechanical Turk (MTurk) in 2005. Clients advertise small projects that cannot be fully carried out by computers. Workers – called "turkers" – complete those one-time tasks, for sums ranging from as little as USD 0.01 for a short task to USD 100 for more complex jobs. Currently, some 500 000 workers from 190 countries are registered at Amazon MTurk. Particularly for people living in developing countries, MTurk and similar services have been highlighted as an economic opportunity. For example, Samasource, a non-profit organisation, provides data-related services to large companies in the United States and Europe.

Box 2.9. **Crowdsourcing of human intelligence tasks: "Human computing"** *(cont.)*

It divides work into small batches and sends these for completion to delivery centres in developing countries (Gino and Staats, 2012).

While they represent job opportunities for some, MTurk and similar services such as Samasource have been criticised by some as "digital sweatshops", given that, in the words of one scholar, these services "[circumvent] a range of labor laws and practices, found in most developed countries" (Zittrain [2009], cited in MIT Technology Review [2010]). So-called "micro-workers" typically earn below average hourly wages (Uddin, 2012; Cushing, 2013; Horton and Chilton, 2010). But a survey of working conditions as perceived by 200 workers on MTurk suggests that the workers believe their chances of being treated fairly are as good, or better, online as they are offline (MIT Technology Review, 2010; Horton, 2011). However, issues related to worker conditions remain, despite a 2014 petition from MTurk workers to Amazon CEO Jeff Bezos calling for improved conditions (Harris, 2014; Dholakia, 2015).

Source: OECD (2015b), *Data-Driven Innovation: Big Data for Growth and Well-Being*, *http://dx.doi.org/10.1787/9789264229358-en*.

Large warehouses, which have so far been major employers, are an example of such a system. Many warehouses today use digital technology to direct workers to particular shelves and instruct them on the items to pick. The worker then scans the barcodes of the items picked and deposited. Workers walk many kilometres each day.[20] Other warehouses use conveyor belts for products. The humans are controlled by computers. However, in some of the warehouses, the model of working has changed. In these warehouses the shelves come to the workers, carried by small driving robots such as those manufactured by Kiva Systems, a company acquired by Amazon after it started using Kiva's robots. Kiva Systems creates a different type of warehouse, where workers stand still and the shelves are dynamic. The location of goods is continuously optimised, so that the most popular products are situated on the shelves that need to travel the shortest distance.[21] A laser shows the worker what product needs to be picked and where it needs to be deposited. The effect is a highly efficient warehouse that needs fewer workers to handle the same volume of orders.

New policy opportunities and challenges lie ahead

Despite its potential benefits, the digitalisation of industrial and agricultural production still falls short of its potential. There are a number of concurrent reasons for this, as the case of the adoption of precision farming technology in the Netherlands shows (Box 2.10). This section will discuss the key policy issues which, if properly addressed, can maximise the benefits of digitalisation.

Box 2.10. **Drivers and challenges in the adoption of precision farming technologies**

The concept of precision farming has captured the imagination of industry and policy makers, even if the market for precision farming solutions is still young.

In a survey of Dutch farmers about 55% of respondents indicated that they own tools that support precision farming (University & Research Centre, WUR). Most commonly these were GPS-equipped tractors and, to a lesser extent, tools that monitor crops and soil.

Box 2.10. **Drivers and challenges in the adoption of precision farming technologies** *(cont.)*

However, the integration of machine-generated data into business management systems (BMSs) is limited. The use of BMS by farmers is primarily driven by existing regulatory and customer requirements regarding food safety. In other words, these tools are mostly used for registration purposes rather than for yielding actual management information. BMS becomes more valuable to farms as they grow in size and require better information processing. About 45% of respondents use collected data for planning fertilisation, irrigation and pesticide spraying. However, planning such activities is not generally based on real-time data collected and processed automatically by machines. In other terms, the full potential of the technology is not being exploited.

The ease of use of ICT tools, and farmers' ICT skills, are the most important factors driving the adoption and use of precision farming technologies. Other influences are farm size, the opportunities for cost reduction, total farm income, land tenure arrangements, access to information (via extension services and service and technology providers), and location (Perpaoli et al., 2013).

Adoption rates for precision farming vary across sub-sectors. Various sources suggest that the use of data and data analytics in livestock farming, and in greenhouses, is more advanced than in crop farming. This could be because the former two sectors have shorter production cycles and operate in controllable environments, which makes precision farming solutions and automation more profitable.

Another important enabler of diffusion is the penetration of (mobile) broadband. The European AgriXchange research project concluded that the lack of broadband in many rural areas in Europe is an important barrier to innovations that build on the collection and exchange of data.

Overcoming barriers to ICT diffusion, interoperability and standards

The digitalisation of industrial production requires the diffusion of key ICTs, particularly among SMEs. However, many businesses lag in adopting ICTs. For example, the adoption of cloud computing, SCM, ERP, and radio-frequency identification (RFID) applications by firms is still much below that of broadband networks or websites (Figure 2.7). Nevertheless, it is these advanced ICTs that enable the digitalisation of industrial production.

Factors preventing firms from using advanced ICTs include technological lock-ins,[22] often due to proprietary solutions, a lack of (open) standards, and risks of security breaches (large firms in particular express concerns about data security). In addition, smaller firms often have difficulties to implement organisational change, due to limited resources, including the shortage of skilled personnel.

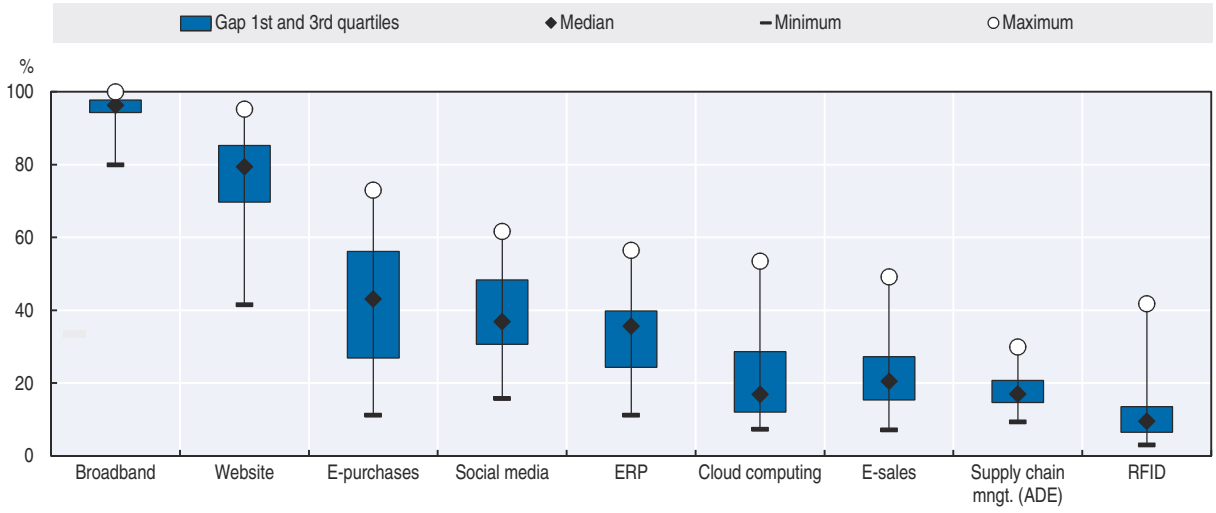
Device identification is one of the most important aspects of interoperability. In particular, achieving interoperability among heterogeneous identifiers may prove to be a challenge for deployment of the IoT. This is because the IoT concerns billions of objects that are a part of existing Internet-based networks and which need to be uniquely addressable.

Another interoperability issue will arise when users attempt to use IoT devices and applications from different manufacturers and suppliers. This may raise problems, e.g. when using IoT applications on different systems or networks – say from one country to another – or moving a device such as a car to a new service provider or network. A World Economic Forum executive survey (WEF, 2015) confirms that lack of interoperability ranks among the top three barriers

to IoT adoption (after security concerns, but before uncertainty in the return on investment). Furthermore, there is evidence that most data generated by sensors do not reach operational decision makers due to interoperability issues (McKinsey Global Institute, 2015).

Figure 2.7. **Diffusion of selected ICT tools and activities in enterprises, 2015**

Percentage of enterprises with ten or more persons employed



Source: Based on OECD (2017b), *OECD.Stat*, database, *http://dotstat.oecd.org/index.aspx?DatasetCode=ICT_BUS* (accessed March 2017).

StatLink http://dx.doi.org/10.1787/888933473783

Regulatory barriers may also prevent the effective adoption of some ICTs. For example, large-scale IoT users such as car manufacturers which need to control the SIM cards in their cars cannot do so in many countries. Consequently, once a car has a SIM card from a mobile network, the car manufacturer cannot leave the mobile network for the lifetime of the device. Therefore, users with large number of devices (sometimes referred to as million-device users) can effectively be locked into long-term (often 10- to 30-year) contracts. It also means that when a car crosses a border, the large-scale user is charged the operator's costly roaming rates.

Addressing potential skills bottlenecks

The increasing use of advanced ICTs, such as data analytics, has raised demand for new types of skills. A scarcity of specialist skills may hinder adoption of ICTs. For example, surveys point to the shortage of skilled data specialists as one of the biggest impediments to the use of data analytics in business. In the United States, since 1999, occupations for those with advanced ICT skills have been among those with the fastest growth in relative wages, suggesting (combined with other evidence) a possible shortage of such skills.

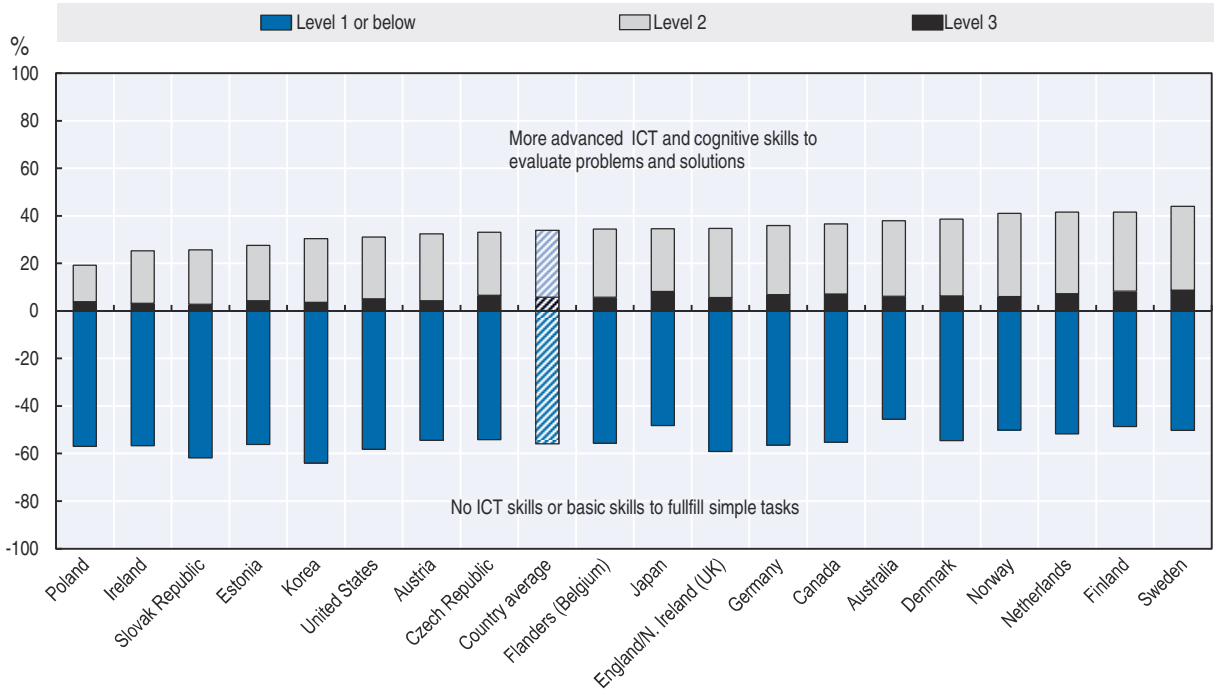
Many countries are struggling to develop the necessary skills. OECD data reveal that 7% to 27% of adults in OECD countries still have no experience in using computers, or lack the most elementary skills. Only 6% of people in the OECD[23] have the "highest level" of ICT skills. In countries such as Austria, the United States, Korea, Estonia, the Slovak Republic, Ireland and Poland, the share is 5% and below (Figure 2.8).

Evidence also strongly suggests that geography plays a role. For example, most of the big-data technologies, such as Hadoop, are so new that few experts have sufficient knowledge or the expertise to work with them, and those with high levels of skills tend to concentrate in regions such as the San Francisco Bay area in the United States. These

findings call for cautious interpretation of country-level employment and skills statistics, as the latter do not always reflect (sub-) regional labour market dynamics and skill gaps.

Figure 2.8. **Level of proficiency in problem solving in technology-rich environments, 2012**

As a percentage of 16-65 year-olds



Note: Problem solving in technology-rich environments requires "computer literacy" skills (i.e. the capacity to use ICT tools and applications) and the cognitive skills required to solve problems. Level 1 or below possesses no ICT or basic skills to fulfil simple tasks; levels 2 and 3 require more advanced ICT and cognitive skills to evaluate and find solutions.

Source: OECD (2014b), *OECD Science, Technology and Industry Outlook 2014*, *http://dx.doi.org/10.1787/888933151932*, based on OECD's Programme for the International Assessment of Adult Competencies (PIAAC).

StatLink *http://dx.doi.org/10.1787/888933473793*

A scarcity of technical skills can often result in a lack of awareness of the productive potential of ICTs. This is particularly true for firms that face challenges in transforming their organisation. A recent study (Hammermann and Stettes, 2016) on the impact of digital change on skills and employment in Germany suggests that the "ability to plan and organise, to act autonomously", combined with firm-specific and occupation-specific working experience, are crucial for the successful digital transformation of businesses. However, surveys also show that the ability to articulate the value of digitalisation for a business' future is often missing. This translates into the lack of a business strategy for digital transformation. Kane et al. (2015), for example, find that "early-stage companies are often falling into the trap of focusing on technology" and thus only use ICTs for improving their operations, if they use ICTs at all, instead of using ICTs to transform their business. Only 52% of businesses which use ICT less intensively (early-stage adopters) say that transforming the business is part of their digital agenda.

Considering data as a new infrastructure for 21st-century production

Data are an infrastructural resource. Data represent a form of capital that can be used for a theoretically unlimited range of purposes. Physical infrastructure such as roads and

bridges helps the economic benefits of some activities to "spill over", e.g. by fostering trade and social exchanges. The use of data also generates spillovers across the economy. But some of the spillovers from data are not easily observed or quantified (for example greater levels of trust induced by transparency and data-driven applications, as both are enabled by open public sector data). As a result, countries could risk under-investing in data and data analytics and may end up giving access to data for a narrower range of uses than is socially optimal. This risks undermining countries' capacity to innovate, as data and its analysis have become fundamental to innovation.

The value of data depends on the context of their use, on the use of complementary assets such as data analytics and other (meta-) data, as well as on the extent to which data can be reused. There are therefore at least three means through which the value of data can be maximised, namely by:

- enhancing the quality of data to make them a better "fit for use"
- enhancing data analytic capacities by investing in analytic software, know-how and skills as well as complementary (meta) data that help enrich existing data
- enhancing access to data to leverage their infrastructural nature (as a non-rivalrous general-purpose productive asset).

Where the social value of data is greater than their private value, benefits can come from enhancing access through e.g. open (non-discriminatory) access to public (open data) data portability or data commons.

Preserving the open Internet for global value chains

Data and digital services are increasingly traded and used across sectors and national borders. Indeed, companies increasingly divide their digital processes – hosting, storage and processing – across many countries.

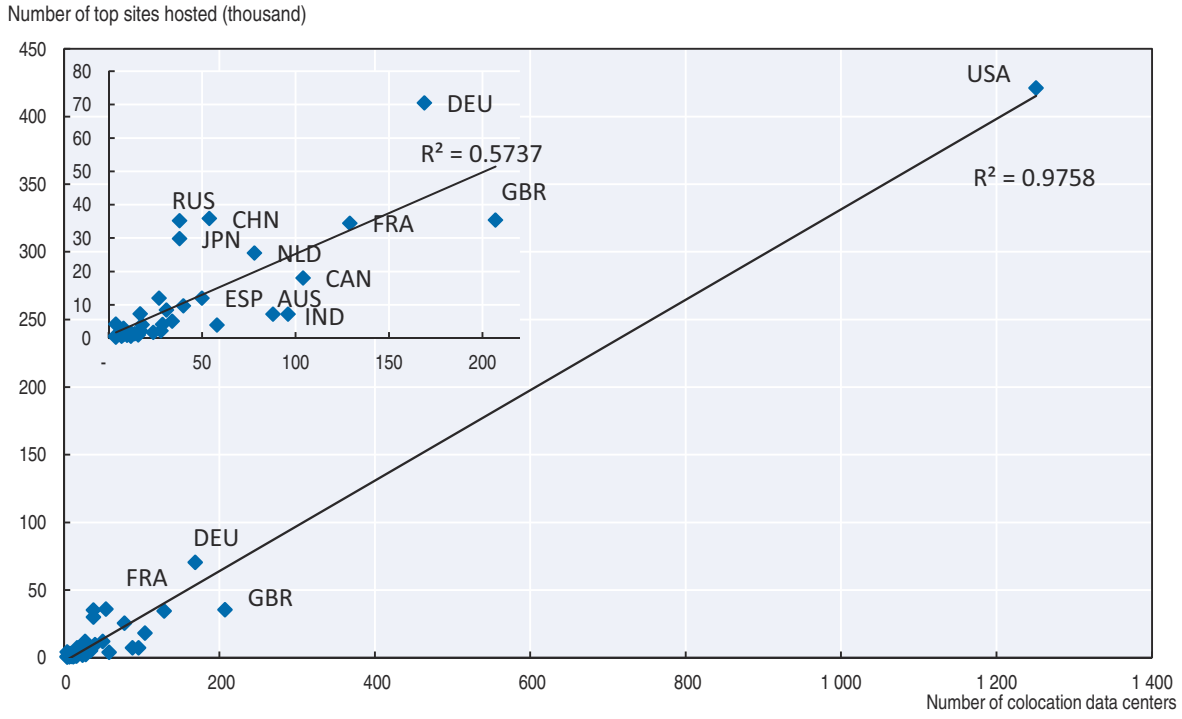
The precise distribution of digital services globally, and the magnitudes of cross-border data flows, are not known. But analysis of the world's top Internet sites suggests that digital services are disproportionately concentrated in the United States, which alone accounted for more than 50% of all top sites hosted in the OECD area in 2013 (Figure 2.9). Canada, Germany, France, Ireland, the Netherlands, Japan and the United Kingdom, as well as China, India and the Russian Federation, are catching up as they increase their contribution to global trade in ICT-intensive services.

Countries with the largest numbers of top Internet sites are also those that have the highest number of co-location data centres (data centres that are shared between users). They are also the leading locations for data-intensive services. Major exporters of digital services and top locations for data-driven services are likely to be major destinations for cross-border data flows. As a consequence, the leading OECD area importers of ICT-related services are also the major sources for trade-related data exchange. These countries thus heavily rely on cross-border data exchange.

Encouraging investments in R&D in key enabling ICTs

The digitalisation of industrial production requires investments in R&D in digital goods and services including, but not limited to, the IoT, data analytics, and computing. Countries with enhanced capacities to supply and adopt these goods and services will be in the best position to benefit from first-mover advantages coming from the digitalisation of production.

Figure 2.9. **Top locations by number of co-location data centres and top sites hosted, 2013**

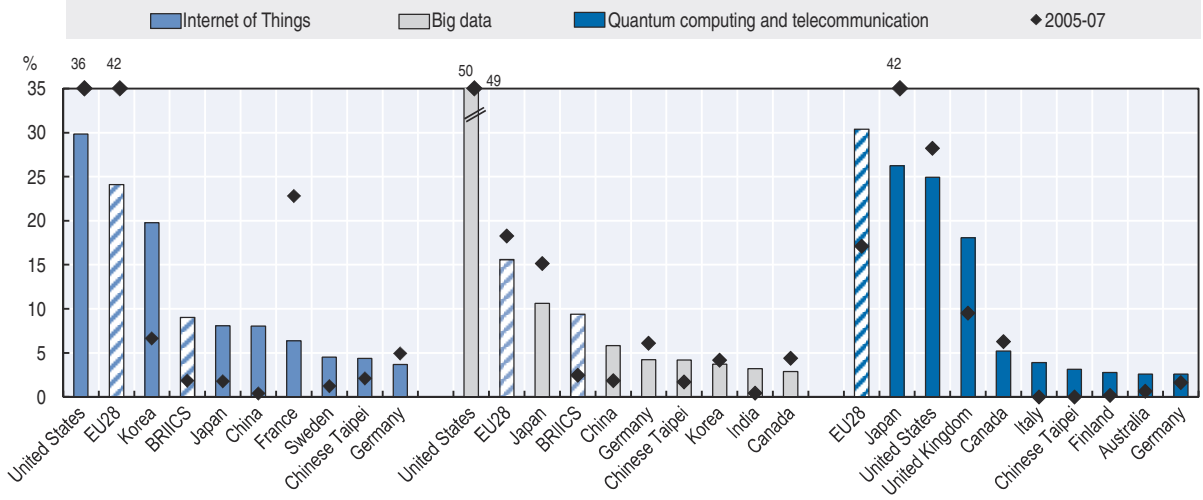


Sources: Based on Pingdom (2013), "The top 100 web hosting countries", *http://royal.pingdom.com/2013/03/14/web-hosting-countries-2013/* (accessed 19 May 2015) and *www.datacentermap.com* (accessed 27 May 2014).

StatLink http://dx.doi.org/10.1787/888933473803

Figure 2.10. **Top players 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 (2015c), *OECD Science, Technology and Industry Scoreboard 2015*, *http://dx.doi.org/10.1787/sti_scoreboard-2015-en*, based on IPO (2014), "Eight great technologies: the patent landscapes", *www.gov.uk/government/uploads/system/uploads/attachment_data/file/360986/Eight_Great_Technologies.pdf* (accessed June 2015).

StatLink http://dx.doi.org/10.1787/888933473815

Data on international patent filings provide evidence that inventive activity in technologies related to the digitalisation of industrial production is rapidly increasing. Since 2007, the number of patent filings related to the IoT, big-data analytics, and quantum computing and telecommunication has grown at two digit rates. In 2012, the latest year for which data are available, growth reached more than 40%. But the supply of DDI-related technologies is concentrated in only a few economies, with the United States leading in terms of the number of filed patents, followed by Canada, France, Germany, Korea, Japan and the United Kingdom, as well as China (Figure 2.10).

Addressing liability, transparency, and ownership issues

Data analytics leads to new ways of decision making, through low-cost and rapid experiments, often based on correlations, as well as through the use of AI in autonomous machines and systems. This can lead to accelerated decision making and higher productivity.

But data-driven and AI-enabled decision making can also produce mistakes. This might be because of poor-quality data, errors from the inappropriate use of data and analytics, or unexpected changes in the environment from which data are collected. Recent financial losses caused by unforeseen behaviour in algorithmic trading systems, such as Knight Capital Group's loss of USD 440 million in 2012, illustrate this last point.

The risk of erroneous decisions raises questions of how to assign liability between decision makers and the providers of data and ICTs. The issue is exacerbated by challenges linked to the concept of data ownership. In contrast to other intangibles, data typically involve complex assignments of different rights across different stakeholders. Where data are considered personal, the concept of ownership is problematic, since most privacy regimes grant explicit control rights to the data subject to the data not being restricted (see for example the Individual Participation Principle of the *OECD Guidelines Governing the Protection of Privacy and Transborder Flows of Personal Data*). For example, data generated from smart meters are considered personal data when they convey information about individual electricity consumption, which challenges any exclusive property right the smart meter owner might claim on the data.

As data analytics and AI-enabled applications become more pervasive, users need to be aware of the limitations of both, or these applications may cause social and economic harm. This is especially true when the incentives for users of these applications to minimise risks to third parties is low. This can happen when analysis of personal data primarily benefits the customer of the application user and not the individuals from whom the data has been collected.

Rethinking policy and regulatory frameworks: from privacy to intellectual property (IP) protection, competition and taxation

Big-data analytics, cloud computing and the IoT could raise serious concerns relating to privacy, IPRs, consumer protection, competition and taxation. Aspects of existing regulatory frameworks may be ill-suited to deal with the new challenges. Further consideration should be given to evaluating opportunities and challenges entailed by existing regulatory frameworks in the transition to digital industrial production.

Comprehensive data collection enabled by the IoT may lead to loss of privacy, with advances in data analytics making it possible to sometimes infer sensitive information, including from non-personal data (e.g. metadata). The misuse of this possibility can affect

core social values and principles, such as individual autonomy, equality and free speech. Meanwhile the applicability of core principles on which privacy protection relies (e.g. the definition of personal data and the role of consent) is being challenged by the huge volume, velocity, and variety of the data being collected almost everywhere.

Data-driven innovation also raises challenges for competition authorities. These include challenges in:

- Defining the relevant market – the use of data enables the creation of multi-sided markets. Typical examples include online platforms such as Facebook and Uber. However, the traditional approach to market definition generally focuses on one side of the market.
- Assessing the degree of market concentration (this relies on the analysis of market prices, however, a large share of data-driven products are provided either for "free" in exchange for access to personal data, and/or in addition to an offer of a bundle of premium services).
- Assessing potential consumer detriments due to privacy violation – competition authorities tend to direct specific privacy issues to the privacy protection authorities, which however have no authority over competition issues (see OECD [2015b]).

Furthermore, data and ICT use across borders can make it difficult for tax authorities to determine where tax-relevant activities are carried out and where value is created (OECD, 2015a). Inherent in this is the difficulty in measuring the monetary value of data, determining data ownership, and acquiring a clear picture of the global distribution and interconnectedness of data-driven services.

Finally, the convergence of production infrastructure with ICTs, and the increasing role of software, give IPR, and in particular copyright, a strategic role as a point of control in future production. Recent OECD (2015d) work already showed that, among the different types of IPRs, copyright's performance excels in terms of the magnitude of investment it attracts, the growth rate of that investment, and the associated job growth. Copyright's economic importance appears to be growing. In particular, in much of the world copyright protects a significant amount of software investment.

The increasing role of IPRs for the future of manufacturing also comes with challenges. Concerns have been raised that the control of strategic IPRs on which whole ecosystems rely today could favour anti-competitive behaviour. This remains true despite the increasing use of open-source software (OSS) applications, which have eased some of the constraints that IT infrastructure users faced in the past (see OECD [2015b]). For example, some have expressed concerns that the patent US 7650331 B1 on MapReduce[24] awarded to Google could put at risk companies that rely on the open-source implementations of MapReduce such as Hadoop and CouchDB. But given that Hadoop is widely used today, including by large companies such as IBM, Oracle and others, as well as by Google, many consider that Google "obtained the patent for 'defensive' purposes" (Paul, 2010).[25] By granting a licence to (open-source) Apache Hadoop under the Apache Contributor License Agreement (CLA), Google has officially eased fears of legal action against the Hadoop and CouchDB projects (Metz, 2010).

Another area related to ICT-enabled production systems where IPRs might play a role are APIs. Copyright protection for APIs could help to deter counterfeit applications. Not only does copyright protection provide incentives for investment and innovation in applications, it also promotes cybersecurity since counterfeit applications may be used to introduce malware in production systems. However, some experts have raised concerns that copyrighting APIs could also adversely affect the creation and adoption of new

applications, and that control of IPRs related to APIs could lead to anti-competitive behaviour.[26] Trends towards more closed APIs are therefore raising concerns among some actors that rely on open APIs for their innovative services.

Policy considerations

Based on the discussion in the previous section a number of policy considerations can be derived. These policy considerations can be clustered around three objectives: first, promoting investments in ICT and data, including investments in complementary organisational change; second, supporting the development of skills and competences for the digitalisation of production; and, third, addressing emerging risks and uncertainties, related either to the use of new digital technologies or to inefficiencies in current regulatory frameworks.

Promoting investments in and use of ICT and data

- **Governments aiming to promote the supply of key ICTs should consider supporting investments in R&D in enabling technologies** such as big-data analytics, cloud and high-performance computing, and the IoT, as well as in security- and privacy-enhancing technologies. Through its 2014 national digital economy strategy, Canada, for example, foresees investments worth CAD 15 million over three years to support leading-edge research in, and the commercialisation of, quantum technologies. And France intends to invest EUR 150 million to support R&D in five technologies identified as strategic: the IoT, super and cloud computing, big-data analytics, and security.
- **Governments should consider using demand-side policies to encourage the 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 (Box 2.11). These measures should also aim at fostering investments in complementary forms of knowledge-based capital (KBC), including in particular organisational change (see OECD [2016b]). Demand-side policies should also be complementary to (existing) ICT supply-side policies (e.g. R&D programmes and national broadband strategies). In Germany, for example, policies supporting investments in R&D related to industrial ICT applications, IT security research, microelectronics and digital services, are complemented with demand-side policies such as awareness raising and training (e.g. through two big-data solution centres established in Berlin and Dresden). Furthermore, the German government has gathered more than 260 examples of the successful implementation of "Industry 4.0" in an interactive online map.[27]
- **Governments should develop an innovation policy mix that encourages investments in data** (its collection, curation, reuse and linkage) that have positive spillovers across industries, while addressing the low appropriation of returns to data sharing. This is particularly relevant for data with social value that is larger than private value. To address the appropriation challenge, the combination of IPR, licences and alternative incentive mechanisms such as data citations, data donation or philanthropy, need to be considered further. One example of where alternative incentive mechanisms have been effective is in science and research. Researchers wishing to be acknowledged for their work can release data sets through mechanisms similar to those already in place for citations of academic articles. However, data citation is still not a widely accepted concept in the academic community.

- **Promoting open standards, including in APIs and data formats, can be key.** Standards based on pro-competitive and technologically open reference models could be promoted to boost the interoperability and reuse of data and digital services, and to reduce technological lock-ins, while enhancing competition among service providers (see OECD [2015a], Chapter 2). For example, the Information Economy Strategy of the United Kingdom aims at "ensuring that key building block standards are deployed – to enable businesses to easily build innovative systems which remain open to further new ideas". The government in the United Kingdom is therefore working through ETSI, BSI and other bodies in the standards field, to bring together a range of stakeholders to align programmes, to build on existing knowledge and to put the United Kingdom in the best position to influence future standards at an international level. The German government, as another example, is promoting standards to ensure interlinking between traditional industries and the ICT sector (Box 2.11).

Box 2.11. **Selected government initiatives promoting ICT adoption by SMEs**

Many governments have initiatives to promote ICT adoption by SMEs, some as part of their national digital strategies, others through separate strategies and programmes. These initiatives are often motivated by the recognition that insufficient knowledge and financial resources, but also barriers to organisational change, often inhibit the effective use of ICTs. In particular, smaller firms, which too often do not have internal IT departments or in-house know-how, are affected as they lack the financial and other resources needed to invest in ICTs or to engage with external ICT services firms. Most initiatives targeting SMEs focus on: awareness raising and training, often with a focus on enhancing ICT-related, and sometimes also organisational, know-how; financial support; and, social networking.

In Canada, for example, the Business Development Bank of Canada (BDC) realigned its existing support to SMEs in 2011 to focus on ICT adoption. Its support is designed around three stages:

- awareness raising, in particular via e-books and articles, success stories and testimonials, and free ICT assessment of a company's technology situation in relation to other Canadian SMEs
- financial support for consulting services to help SMEs tailor ICT solutions to their business, and to address financial challenges more specifically
- loans to purchase hardware, software and consulting services (with a budget of CAD 200 million).

Interest in and use of these offerings has been greater than expected. In the first 18 months of the initiative's existence, from October 2011 to May 2013, the BDC SmartTech website had almost 220 000 visitors; the two e-books were downloaded over 10 000 times; and BDC undertook more than 35 000 online web assessments, around 900 ICT assessments, and over 300 consulting mandates. In addition, BDC averaged 130 ICT loans per month. However, the BDC only serves a small and specific segment of the SME market in Canada, and many other firms would benefit from these services.

Another example is the initiative "Mittelstand-Digital" (EN "SMEs digital") of Germany's Federal Ministry of Economic Affairs and Energy (Bundesministerium für Wirtschaft und Energie, BMWi). This initiative aims to show SMEs and skilled crafts people the importance of using software for business processes, and give support for digitalising these businesses. The initiative builds on three pillars, including:

Box 2.11. **Selected government initiatives promoting ICT adoption by SMEs** *(cont.)*

- **German Mittelstand 4.0 – digital production and work processes**, which aims to support SMEs and skilled crafts people in digitalising business processes and deploying Industry 4.0 applications via competence centres. Among others, focus is put on raising awareness of opportunities and challenges, enhancing technological and organisational competences, and providing opportunities for demonstration and testing.
- **Simply intuitive – usability for SMEs**, which aims at providing development and testing support mechanisms for SMEs to increase quality and usability of business and production software in SMEs. This pillar is motivated by the recognition that software for SMEs has mostly ignored aspects of usability, which, however, has become an important aspect of end-user software.
- **e-standards – standardising business processes, securing success**, which aims at developing a common language for SMEs and different fields of business so as to facilitate data exchange. This pillar is motivated by the finding that SMEs face considerable initial costs if they want to use and implement e-standards.

The initiative "Mittelstand-Digital" so far shows that trust is important for SMEs. Unbiased, official information produced by the federal government has found broad acceptance, while information provided by commercial IT consultants is seen rather sceptically. Creating networks between stakeholders, where entrepreneurs can learn from each other, has helped to create acceptance among SMEs.

In Korea, as another example, 17 creative economy and innovation centres have been created nationwide to promote digital innovation. A significant number of centres focus on digital innovation in production. Local governments and big Korean corporations (e.g. SKT, Hyundai-Kia, GS, Doosan, LG, Samsung and Lotte) jointly operate the regional centres. The tasks of these centres include: supporting start-ups and SMEs in each speciality area, organising the partnership or ecological relations between the relevant big corporations and regional enterprises, arranging funds for them to overcome financial difficulties, encouraging managerial and technological innovation and advisory services (called mentoring), promoting communication and co-operative work among participants, and exploring new markets at home and overseas.

Source: OECD (2016b), "Stimulating digital innovation for growth and inclusiveness: The role of policies for the successful diffusion of ICT", *http://dx.doi.org/10.1787/5jlwqvhg3l31-en*.

Supporting the development of skills and competences for the digitalisation of production

- 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 data specialist skills. Related educational needs extend beyond ICT to include science, technology, engineering and mathematics (STEM). This calls for measures to: promote digital literacy in schools; further develop vocational and on-the-job training; and interlink educational areas, e.g. through the establishment of strategic alliances between universities and businesses as well as interdisciplinary competence centres. Examples include two big-data solution centres established in Berlin and Dresden in the context of Germany's national digital economy strategy (Digital Agenda 2014-17).
- **Technical skills alone are not enough.** Technical skills need to be complemented with know-how on domain-specific issues (including know-how about the entire production

process) as well as "soft skills" such as communication, self-direction, creative thinking and problem solving. OECD (2016d) shows that demand for such non-technical skills will continue to grow as the diffusion of digital technologies and new business models change how work is performed. These skills are particularly important to address the effects of technologies that are disrupting existing industries. Those with low skills are more likely to be displaced, so improving their non-technical skills will help them to adapt to new occupations and new workplaces. Businesses and their social partners also have important roles to play, as illustrated by the best-practice examples published by the German government on how to implement training and develop qualifications in companies.[28]

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 that have been designed for the pre-digitalised world were to inadvertently shield incumbents from competition that digitalisation could bring, thereby thwarting digital innovation (see OECD [2017a]). For the IoT, for example, removing regulatory barriers to entry into the mobile communication market would allow the so-called 'million-device users', such as some vehicle manufacturers, to become independent of the mobile network, strengthening competition (see OECD [2016a]). To take another example, in the automobile and mobility services industry, existing taxi regulations may slow the diffusion of mobility services (including ride sharing) applications, and may require review and reforms to permit application-based ride services to continue. Similarly, already available technical solutions for self-driving trucks cannot often be deployed because of existing regulatory frameworks.
- **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*. Otherwise, stakeholders will continue to adopt a traditional security approach that not only falls short of appropriately protecting assets in the current digital environment, but is also likely to stifle innovation and growth (see OECD [2016c]). The usual barriers to a culture of digital risk management in businesses, and in particular SMEs, are a lack of know-how related to digital risk management and the misunderstanding that digital security is a (technical) IT management issue, rather than a business management issue. To respond to this challenge, governments have prioritised awareness raising, training and education on digital risk management. The French national digital security strategy, for example, foresees that the French state secretariat in charge of digital technology, along with the ministries concerned, should co-ordinate, with the support of the Agence nationale de la sécurité des systèmes d'information (National Cybersecurity Agency, ANSSI), the establishment of a cybersecurity awareness-raising programme for professionals in France.
- **Barriers to Internet openness, legitimate or otherwise, can limit the effects of digitalisation and may require policy attention.** Frequently encountered barriers include technical means, such as IP package filtering, which is used among other things to optimise the flow of data for specific purposes, and "data localisation" efforts, such as territorial routing or legal obligations to locate servers in local markets. The limiting effects of barriers to Internet openness are particularly severe in economies where deployment of data-driven services is poor due to failures in ICT infrastructure markets. However, as highlighted in OECD (2016e), openness also presents challenges, as some

actors may take advantage of it when conducting malicious activities. Barriers to Internet openness coming from business practices or government policies may thus have a legal basis, such as the protection of privacy and IPRs, as well as a security rationale. Governments looking to promote trade in digital services should take the OECD 2011 *Council Recommendation on Principles for Internet Policy Making* into consideration. These principles aim to preserve the fundamental openness of the Internet and the free flow of information.

- **Obstacles to the reuse, sharing and linkage of data should be examined.** These obstacles can include technical barriers, such as constraints on the machine readability of data across platforms. Legal barriers can also prevent data reuse, sharing and linkage. For example the "data hostage clauses" found in many terms-of-service agreements can be a legal barrier, in particular when this provision is "used to extract additional fees from the customer or to prevent the customer from moving to another provider" (Becker, 2012).[29] Non-discriminatory access to data (or "access on equal terms"), including data commons or open data, as well as data portability, should be explored to support the production of goods with public and social benefits without requiring governments or businesses to pick winners (whether users or applications) (Box 2.12).
- **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 in the application and enforcement of data governance and IPR frameworks. So far no commonly agreed data governance framework exists that would support the reuse, sharing and linkage of data across sectors. Issues that would need to be addressed by such a framework could include, among others, questions related to accountability, data ownership, data curation and the repurposed reuse of data. In the context of business-to-business (B2B) transactions, these questions could potentially be, and often are, addressed by bilateral contractual arrangements. However, even then standards and best practices are needed to reduce exposure to digital risks in supply chains.
- **Governments may seek to promote the responsible use of personal data to prevent violations of privacy.** Efforts to promote privacy-enhancing technologies and the empowerment of individuals through greater transparency of data processing, and through data portability, via such initiatives as midata (United Kingdom) and MesInfos (France) should be further considered. Governments may need to increase the effectiveness (i.e. resourcing and technical expertise) of privacy enforcement authorities. Data protection regulations should aim to offer a high level of privacy protection and be easily implementable, with the goal of widespread adoption.
- **Governments may need to assess market concentration and competition barriers** using up-to-date definitions of the relevant market and taking into consideration potential consumer detriment due to privacy violations. It may be necessary to foster dialogue between regulatory authorities (in particular in the area of competition, privacy and consumer protection) as highlighted in OECD (2015a, Chapter 2).
- **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 through the exchange of best practices and helping to develop compatible approaches to addressing these challenges.

Box 2.12. **Improving agricultural performance with open data: The case of US Department of Agriculture (USDA)**

As farming is becoming increasingly data-driven, farmers need data to be competitive. For entry-level farmers, who may not own historical data, lack of data could become a competitive disadvantage.

To address this challenge, the USDA has made its data openly available. These include data on food supply, economic demand, and remote sensing that are made available as part of the USDA's National Agricultural Statistical Service (NASS) and its Economic Research Service (ERS). Many data sets span the past 100 years and are provided through APIs. NASS offers, for example, a CropScape API that provides direct access to a raster image dataset containing an agriculture-specific land cover classification published annually at the end of the growing season, as well as a VegScape API that provides direct access to a raster image dataset on crop condition vegetation, published on biweekly timescales throughout the year. USDA also provides ERS data on farm financial and crop production practices, including data on production practices and costs (such as fertiliser, pesticide, labour, tillage and seeds) and on financial information for farm businesses, as well as a variety of financial and demographic information (such as age, education, occupation, off-farm income) for farm operators and their households.

To promote the reuse of its data, USDA, in collaboration with Microsoft, initiated the Innovation Challenge, a competition (hackathon) to develop data-driven software applications to explore how climate change could affect the resilience of food systems in the United States. USD 63 000 in prizes were offered for applications that use the USDA data and provide actionable insights to farmers, agricultural businesses, scientists, or consumers across the United States. One winning application, FarmPlenty Local Crop Trends, helps farmers find the best crops by browsing nearby crops, trends, and prices: "Using this information, a farmer can better understand what crops are becoming more popular or unpopular in the region and anticipate changes in prices and demand."[1]

1. See *http://devpost.com/software/farmplenty-local-crop-trends* (accessed 15 January 2017).

- **Also needed is careful examination of the appropriateness of fully automated decision making, transparency requirements and required human intervention in areas where the potential harm of decisions could be significant.** Policy makers should consider that transparency requirements may need to extend to the processes and algorithms underlying automated decisions. These transparency requirements may conflict with existing IPRs and the processes and algorithms at the core of certain business operations. More studies are needed to determine how best to assess the appropriateness of algorithms without violating existing IPRs.
- **Governments may need to encourage improved measurement to help better assess the economic value of data, and to prevent base erosion and profit shifting.** Such base erosion and profit shifting occur through aggressive tax planning by firms seeking to artificially reduce taxable income or shift profits to low-tax jurisdictions by taking advantage of the intangible nature of data, and with that the ease of moving data across jurisdictions (see OECD [2015a], Chapter 2).

Notes

1. Advanced ICTs, such as ERP software, are thought to enhance firm competitiveness by synchronising internal business processes and by providing real-time data for management decision making, thereby reducing structural barriers between departments and allowing for greater collaboration and innovation (for the quantification of the beneficial effects of ERP investments on firm performance see Hitt and Zhou, 2002).
2. Rolls-Royce uses big data to reduce downtime for its engines. Its on-board analytics transmit only data that deviates from normal, so its employees monitor engines while they are in operation. As a result, they can intervene to address any issues before they become big problems that might result in a disruption of service. This approach also supports Rolls' "Power by the Hour," contracts for services. This allows Rolls-Royce to sell engines as a service, not a product (see also Michelin's "kilometre by the hour" offering).
3. This represents an average annual (year-on-year) growth of 1.7%. This potential arises from the sum of the expected additional value-added for mechanical (EUR 23 billion at an expected year-on-year growth of 2.21%), electrical (EUR 13 billion, +2.21%), automotive (EUR 15 billion, +1.53%), chemical (EUR 12 billion, +2.21%), agriculture (EUR 3 billion, 1.17%) and ICT sectors (EUR 14 billion, 1.17%).
4. Figure 2.3 is highly stylised, and does not show many of the complex relationships and feedback loops between these technologies.
5. However, these estimates cannot be generalised, for a number of reasons. First, the estimated effects of DDI vary by sector and are subject to complementary factors such as the availability of skills and competences, and the availability and quality (i.e. relevance and timeliness) of the data used. More importantly, these studies often suffer from selection biases. For example, it is unclear whether the firms adopting DDI became more productive due to DDI, or whether they were more productive in the first place. Furthermore, these studies rarely control for the possibility that some firms may have seen a reduction in productivity due to DDI, and so may have discontinued their investment in it.
6. This estimate uses value-added by industry data from the US Bureau of Economic Analysis. It is part of the *GDP by Industry* database (*www.bea.gov/iTable/iTable.cfm?ReqID=51&step=1#reqid=51&step=51&isuri=1&5114=a&5102=1*).
7. The Fort Hays State study employed a mathematical estimation tool. It studied 1 445 fields with a total of 135 755 acres in three states.
8. Cloud computing can be classified into three different service models according to the resources it provides: infrastructure-as-a-service (IaaS) provides users with managed and scalable raw resources such as storage and computing resources; PaaS provides computational resources (full software stack) via a platform on which applications and services can be developed and hosted; and SaaS offers applications running on a cloud infrastructure. Sometimes clouds are also classified into private, public, and hybrid, according to their ownership and management control.
9. As a result of its simulation, Ford, for example, introduced an aluminium chassis that reduced costs and increased profitability. By some accounts, Ford is making a 50% profit on new F-150 trucks.
10. A report of a stakeholder organisation states that in 2020 benefits of the IoT could be up to USD 2 trillion, whereas USD 1 trillion could be based on cost reductions (e.g. by using smart meters where the estimation is that already 1.1 billion devices could be in use by 2022) and another USD 1 trillion could come from improved services such as remote monitoring of chronically ill patients. These figures are outnumbered by an analysis which predicts that for the car industry alone annual global savings of over USD 5.6 trillion could be achieved by cars based on advanced connectivity technology (semi-autonomous and completely autonomous cars).
11. Driverless cars such as those developed by Google, are based on the collection of data from all the sensors connected to the car (including video cameras and radar systems), which are combined with data from Google Maps and Google Street View (for data on landmarks, traffic signs and lights).
12. A firm that invests USD 1 million on a large-scale enterprise software installation faces a one-time expense that cannot be recovered once spent.
13. See *www.mckinsey.com/industries/high-tech/our-insights/disruptive-trends-that-will-transform-the-auto-industry* (accessed 15 January 2017).
14. While Internet firms among the top 250 ICT firms generated on average more than USD 1 million in annual revenues per employee in 2012 and more than USD 800 000 in 2013, the other top ICT firms generated around USD 200 000 (IT services firms) to USD 500 000 (software firms) (OECD, 2015b).

15. As Mayer-Schönberger and Cukier (2013) explain: "To datafy a phenomenon is to put it in a quantified format so it can be tabulated and analyzed".

16. Infotainment is a portmanteau for information and entertainment. "Typical tasks that can be performed with an in-vehicle infotainment system include managing and playing audio content, utilizing navigation for driving, delivering rear-seat entertainment such as movies, games and social networking, listening to incoming and sending outgoing SMS text messages, making phone calls, and accessing Internet-enabled or smartphone-enabled content such as traffic conditions, sports scores and weather forecasts." (Beal, 2016).

17. Daimler is still seen as one of the leading automobile firms in terms of (semi-) autonomous cars. At the Consumer Electronics Show in Las Vegas in January 2015, Daimler presented its Mercedes F 015, which drove itself onto the showroom floor.

18. "Contract farming can be defined as an agricultural production carried out according to an agreement between a buyer and farmers, which establishes conditions for the production and marketing of a farm product or products. Typically, the farmer commits to providing agreed quantities of a specific agricultural product." (FAO, 2012).

19. For 2030, it is estimated that 8 billion people and maybe 25 billion active "smart" devices will be interconnected and interwoven by one single huge information network, leading to the emergence of an intelligent "superorganism" in which the Internet represents the "global digital nervous system" (Radermacher and Beyers, 2007; O'Reilly, 2014).

20. For example, workers in Amazon's warehouses in the United Kingdom are reported to walk between 11 and 24 kilometres per day (O'Connor, 2013).

21. Before the system can function, it has to model the position of all goods in the warehouse and the most efficient paths and distribution.

22. As Perkins (2003) explains: "Central to the idea of lock-in is that technologies and technological systems follow specific paths that are difficult and costly to escape. Consequently, they tend to persist for extended periods, even in the face of competition from potentially superior substitutes. Thus, lock-in is said to account for the continued use of a range of supposedly inferior technologies, ranging from the QWERTY keyboard to the internal combustion engine."

23. In 2013, ICT investment in the OECD area represented 13.5% of total fixed investment or 2.7% of GDP, with over two-thirds of ICT investment being devoted to software and databases.

24. MapReduce is a programming framework for processing large data sets in a distributed fashion presented in a paper by Dean and Ghemawat (2004). In 2006, the open-source implementation of MapReduce, called Hadoop, emerged. Initially funded by Yahoo, Hadoop is now provided as an open-source solution (under the Apache License) and has become the engine behind many of today's big-data processing platforms. Beside Yahoo, Hadoop is ushering in many data-driven goods and services offered by Internet firms such as Amazon, eBay, Facebook, and LinkedIn.

25. As Paul (2010) explains: "Many companies in technical fields attempt to collect as many broad patents as they can so that they will have ammunition with which to retaliate when they are faced with patent infringement lawsuits." For more on IP strategies see OECD (2015d).

26. The debate on the ability of legal entities to copyright APIs has gained significant momentum after a recent petition by the Electronic Frontier Foundation (EFF, 2014) to the US Supreme Court in November 2014 (see Brief of Amici Curiae Computer Scientists in Support of Petitioner, Google Inc. versus Oracle America, Inc., Supreme Court of the US, No. 14-410, November 7, 2014). The petition follows a court finding earlier in May 2012 that Google had infringed on Oracle's copyright on Java APIs in Android, "but the jury could not agree on whether it constituted fair use" (Duckett, 2014).

27. See *www.plattform-i40.de/I40/Navigation/DE/In-der-Praxis/Karte/karte.html* (accessed 16 January 2017).

28. See *www.plattform-i40.de/I40/Redaktion/DE/Downloads/Publikation/digitale-transformation-im-betrieb-aus-und-weiterbildung.pdf* (accessed 16 January 2017).

29. As Becker (2012) explains: "Data hostage clauses are employed when a contract between a cloud provider and customer is improperly terminated by the customer in order to allow the cloud provider to hold on to a customer's data until the customer has paid a termination fee or compensated the cloud provider for lost business through liquidated damages. In some cases, however, this data hostage provision may be used to extract additional fees from the customer or to prevent the customer from moving to another provider."

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PART I

Chapter 3

Bioproduction and the bioeconomy

by
The OECD Secretariat

Industrial biotechnology involves the production of goods from renewable biomass instead of finite fossil-based reserves. Much progress has occurred in recent years in the tools and achievements of industrial biotechnology. Industrial biotechnology demonstrates that environmental protection can accompany job creation and economic growth. There are, however, several barriers to its deployment over a wide range of products. Some of these barriers are technical and need further research and development. Others stem from the fact that bioproduction is in direct competition with the fossil oil, gas and petrochemicals industries, which are many decades old, have perfected supply chains, large-scale economies, and receive subsidies. Yet another barrier concerns uncertainty about the sustainability of biomass as a feedstock for future production. Many types of policy are needed to realise the potential of bio-based production, from public support for research, to development of sustainability measures for biomass, to product labelling schemes for consumers, to education and training initiatives for the workforce.

The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Introduction

More than ever before, expanding the bioeconomy is critical. Momentum has been building for over a decade, and events in 2015 – such as COP21 and the Global Bioeconomy Summit – have propelled the bioeconomy concept to the forefront of politics. These events, and the development of the United Nations (UN) Sustainable Development Agenda, came about in response to the "grand challenges" of climate change, energy security, food and water security and natural resource depletion. Expansion of a bio-based economy can help to bring economic growth and environmental policy goals closer together, as well as helping achieve such objectives as rural industrial development. Today, at least 50 countries, including the G7 countries, have national bioeconomy strategies, or have policies steering towards a bioeconomy (El-Chichakli et al., 2016).

Industrial biotechnology involves production from renewable biomass instead of finite fossil-based reserves. The biomass can be wood, food crops, non-food crops or even domestic waste. Much progress has occurred in the tools and achievements of industrial biotechnology. For example, several decades of research in biology have yielded synthetic biology and gene-editing technologies (synthetic biology aims to design and engineer biologically based parts, novel devices and systems as well as redesign existing natural biological systems). When allied to modern genomics – the information base of all modern life sciences – the tools are in place to begin a bio-based revolution in production. Bio-based batteries, artificial photosynthesis and micro-organisms that produce biofuels are just some among the recent breakthroughs. And in a striking breakthrough reported in early 2017, discussed later in this chapter, scientists have succeeded in synthesising graphene from soy bean oil.

Despite the advent of remarkable new biotechnologies, the largest medium-term environmental impacts of industrial biotechnology will hinge on the development of advanced biorefineries (Kleinschmit et al., 2014). Essentially, a biorefinery transforms biomass into marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat). Based on a recent OECD survey, this chapter provides evidence on approaches being employed across countries to develop advanced biorefineries.

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

Demonstrator biorefineries operate between pilot and commercial scales. Demonstrator biorefineries are critical for answering technical and economic questions

about production before costly investments are made at full scale. But biorefineries and demonstrator facilities are high-risk investments, and the technologies are not proven. Financing through public-private partnerships is needed to de-risk private investments and demonstrate that governments are committed to long-term coherent policies on energy and industrial production.

Little policy support has been given to producing bio-based chemicals, as opposed to bio-based fuels (where initiatives have been in operation for some decades). Bio-based production of chemicals could substantially reduce greenhouse gas (GHG) emissions (Weiss et al., 2012).

Governments should focus on three objectives as regards regulations:

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

Improvements to waste regulation could also boost the bioeconomy. For example, governments could ensure that waste regulations are less proscriptive and more flexible, enabling the use of agricultural and forestry residues and domestic waste in biorefineries.[1] Governments could also take the lead in market-making through public procurement policies.

As this chapter outlines, there are also many targets where governments could support R&D and commercialisation in bioproduction and metabolic engineering (i.e. using genetic engineering to modify the metabolism of micro-organisms in such a way that the micro-organisms make useful products). A case in point would be to support R&D on the convergence of industrial biotechnology with new environmentally benign chemical processes. Another is bringing about a greater use of computation, data analytics and digital technologies in synthetic biology (which involves writing new genetic code) and metabolic engineering.

One of the greatest challenges in bio-based production is its multidisciplinarity. Researchers will need to be able to work together across the disciplines of agriculture, biology, biochemistry, polymer chemistry, materials science, engineering, environmental impact assessment, economics and, indeed, public policy. Research and training subsidies will have to create not only the technologies required, but also a cadre of technical specialists (Delebecque and Philp, 2015). There are some proven ways for governments to help tackle this challenge, as this chapter discusses.

The transition to an energy and materials production regime based on renewable resources will face technical and political obstacles and will take time. Earlier transitions, from wood to coal and then from coal to oil, were not complicated by the need to meet today's global challenges. But today's global challenges make the need for this transition all the more urgent.

A policy framework for the bioeconomy

This chapter has two parts. This first part lays out what an overall bioeconomy policy framework would entail, and classifies the forms of support according to whether they are supply- or demand-side measures. The second part of the chapter provides an overview of

the scope of industrial biotechnology and bioproduction that allows the policy maker to grasp the possible impact this form of manufacturing could have. Everyday objects such as tyres and bottles are already being made using renewable resources. The overarching problem is that of achieving scale of production.

There are many definitions of a bioeconomy. Consistent with OECD (2009), a working definition for the purposes of this text is "the set of economic activities in which biotechnology contributes centrally to primary production and industry, especially where the advanced life sciences are applied to the conversion of biomass into materials, chemicals and fuels".

The global nature of the environmental and related economic challenges

When a country's wealth doubles, its carbon emissions rise by about 80% (UNEP, 2010). At the heart of the environmental challenge is the need to decouple economic growth from environmental degradation: in particular there is a need to drastically cut carbon emissions (OECD, 2009). The G7 has called for as-close-as-possible to a 70% reduction on the 2010 level of carbon emissions by 2050 (G7 Germany, 2015). In common with bioeconomy goals, the climate agreement reached in Paris in 2015 aims to reduce carbon pollution and create more jobs and growth driven by low-carbon investments (UNFCCC, 2015).

For governments and the private sector, it is necessary to see the opportunities implied by resource depletion, not just the threats. Building a bioeconomy offers the chance to rebuild industry and society in a sustainable manner, and create jobs and value-added through exploitation of biomass rather than fossil resources. The United States' National Academy of Sciences (2015) has described this as "a vision of the future" because "the core petroleum-based feedstock is a limited resource and diversification of feedstocks will provide even greater opportunity for the chemical manufacturing industry" (National Academy of Sciences, 2015).

General considerations relating to a policy framework for the bioeconomy

All bioeconomy aspirations depend on supplies of sustainable biomass (Piotrowski, Carus and Essel, 2015). In the post-fossil-fuel world, an increasing proportion of chemicals, plastics, textiles, fuels and electricity will inevitably have to come from biomass, and this will increase competition for land (Haberl, 2015). By 2050, the world will need to produce 50% to 70% more food (UN FAO, 2009), increasingly under drought conditions (Cook, Ault and Smerdon, 2015) and using poor-quality soils (Nkonya, Mirzabaev and von Braun, 2016). Herein lies a major conundrum for the bioeconomy – reconciling the conflicting needs of agriculture and industry (Bosch, van de Pol and Philp, 2015). Inevitably, food needs must come first (El-Chichakli et al., 2016), so the extent to which industrial production can rely on biomass is as yet undetermined (PBL, 2012).

Another issue concerns the sustainability of bio-based products, including biofuels and bioenergy. All biofuels and bio-based products are not equal in this regard. While bio-based products can offer environmental advantages (such as significant savings on greenhouse gas emissions), this cannot be assumed in all instances (Posen, Jaramillo and Griffin, 2016). The sustainability of bio-based products needs to be treated on a case-by-case basis (e.g. Urban and Bakshi, 2009; Lammens et al., 2011). In fact, there is considerable variability in estimates of environmental impacts (Montazeri et al., 2016), which is a serious impediment to bio-based production. International standardisation is required for

the credibility of the industry (Carus, 2017). Serious misgivings have also been raised concerning the use of life-cycle analysis (LCA) as the sole tool in environment impact assessment (ANEC, 2012). This is because LCA only measures environmental dimensions of sustainability, omitting economic and social considerations.

Around 50 countries have bioeconomy goals in their economic and innovation strategies. Some have dedicated bioeconomy strategies, including Finland, Germany, Japan, Malaysia, South Africa, and the United States. Still other countries have policies consistent with the development of a bioeconomy, such as Australia, Brazil, the People's Republic of China (hereafter "China"), India, Ireland, Korea, the Netherlands, Russia and Sweden. A comprehensive overview of different national intentions is given in Bioökonomierat (2015). Countries differ in their priorities, some focusing more on health, others on bioenergy. Many express the intention to develop a bio-based industry with products that have higher added value than either biofuels or bioenergy. While national bioeconomy strategies demonstrate intent and commitment, they tend to lack policy detail. Furthermore, the policies affecting the bioeconomy are many, ranging from tax, to industry, agriculture, waste and trade, among others. This breadth increases the challenge of developing a single policy framework for the bioeconomy.

Supply-side, demand-side and cross-cutting measures are all required

Several policy areas are critical. These are grouped in Table 3.1 under three categories (technology push or "supply-side" policies, market pull or "demand-side" policies, and cross-cutting measures). These instruments are considered in detail throughout this chapter.

Table 3.1. **Policy inputs for a bioeconomy framework**

Feedstock/technology push	Market pull	Cross-cutting
Local access to feedstocks	Targets and quotas	Standards and norms
International access to feedstocks	Mandates and bans	Certification
R&D subsidy	Public procurement	Skills and education
Pilot and demonstrator support	Labels and raising awareness	Regional clusters
Flagship financial support	Direct financial support for bio-based products	Public acceptance
Tax incentives for industrial R&D	Tax incentives for bio-based products	
Improved investment conditions	Incentives related to GHG emissions (e.g. ETS)	
Technology clusters	Taxes on fossil carbon	
Governance and regulation	Removing fossil-fuel subsidies	

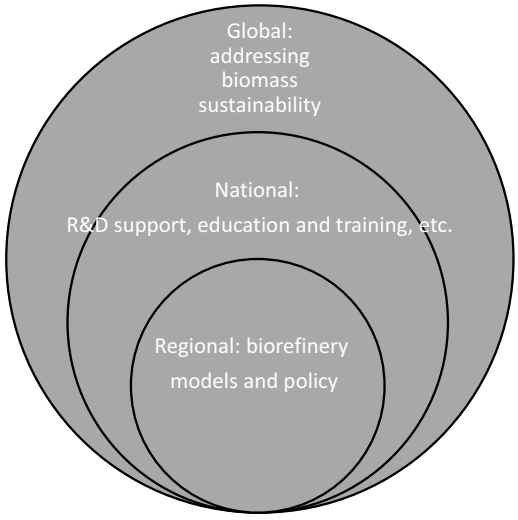
Source: Adapted from Carus, M. (2014), "Presentation at the OECD workshop on bio-based production".

Demand is a major potential source of innovation, yet the critical role of demand as a driver of innovation is not universally recognised by governments (Edler and Georghiou, 2007). In recent years, however, many OECD countries have more often used demand-side innovation policies. These include measures such as public procurement, regulation, standards, consumer policies, and user-led innovation initiatives (OECD, 2011a). Experience in OECD countries has shown that the use of demand-side policies remains limited to areas in which societal needs are not met by market mechanisms alone (e.g. environment) or in which private and public markets intersect (e.g. energy supply). It is relevant, therefore, for bioeconomy policy goals to be both environmentally driven and energy driven.

Policy is needed at multiple scales

The bioeconomy requires multiple scales of policy action (Figure 3.1). These range from regional development, such as biorefinery deployment, through to national R&D support (e.g. for synthetic biology), to the global issues of biomass and its sustainability.

Figure 3.1. **Bioeconomy policy must operate at regional and global levels**



One of the greatest challenges to developing a bioeconomy is that the relevant sectors exist in silos and do not necessarily communicate with each other. For example, the commodities chemicals industry does not routinely interact with farmers. This isolation can be equally true of the policy families in question. What follows is an ordering of policy measures into a potential framework for developing a bioeconomy with regional, national and global reach. Evidence for the need for such a policy framework uses examples from OECD countries and partner economies.

Supply-side policy measures

Supporting R&D and commercialisation in metabolic engineering and bioproduction

The central biotechnology for bio-based materials production is metabolic engineering. Metabolic engineering is the use of genetic engineering to modify the metabolism of micro-organisms. It can involve the optimisation of existing biochemical pathways or the introduction of parts of new pathways. Metabolic engineering is most commonly done in bacteria, yeast or plants, with the aim of achieving high-yield production of specific molecules for medicine or biotechnology.

Despite large numbers of research successes in metabolic engineering, very few new molecules have achieved commercial success. It still takes 50 to 300 people years of work and many millions of dollars to bring a metabolically engineered product to market (Hong and Nielsen, 2012). By comparison, chemistry is way ahead in success rates. There are currently over 30 chemicals derived from biomass at TRL 8 or above (EC, 2015), but few come from metabolic engineering. Rather, they are usually the products of chemistry using biomass as a feedstock.

However, there is emerging evidence that success rates would be higher if governments paid more attention to supporting R&D on the convergence of industrial biotechnology with "green chemistry" (Dusselier et al., 2015). Green chemistry involves designing environmentally benign chemical processes, leading to the manufacture of chemicals with a smaller environmental footprint. Greater success could also come if more R&D was directed towards a higher level of information technology (IT)/computation convergence with synthetic biology and metabolic engineering (Rogers and Church, 2016) (Box 3.1).

Box 3.1. **IT/computation convergence in bioproduction and a universal serial bus (USB) for biotechnology**

Concepts such as interoperability, separation of design from manufacture, standardisation of parts and systems, all of which are central to engineering disciplines, have largely been absent from biotechnology. As a general rule, across industry sectors, around 70% of the costs of manufacturing a product are determined by design decisions, and only 20% determined by production decisions. When the engineering cycle is applied to biotechnology, failure is common.

Manufacturing in the modern economy works because design and testing software can talk to manufacturing hardware via multiple layers of application programming interfaces (APIs). Biotechnology needs to have its own high-level programming language(s) and software to transform the engineering cycle (Sadowski, Grant and Fell, 2016). Interoperability is needed to be able to seamlessly join up the various technologies.

The engineering cycle and biotechnology: the test phase is the bottleneck

When working with vast numbers of genetically engineered micro-orgamisms, evaluating all of their observable characteristics or traits (their phenoptypes) is a major rate-limiting step in metabolic engineering (Wang et al., 2014). When constructing micro-organisms to produce biofuels or bio-based chemicals, design success is measured in the amount of product formed. If this requires the separation of different strains into many separate testing instruments, and the determination of the concentration of the chemical of interest in each, then (only) hundreds of thousands of design evaluations are possible per day. This compares with the possibility of designing and building billions of different genotypes per day (Rogers and Church, 2016). The throughput in the process of evaluating whether the designed organism has the right characteristics is a constraint on overall productivity. Reproducibility in synthetic biology is also a challenge (Beal et al., 2016). This has to be conquered for bio-based manufacturing to become a credible manufacturing platform for the future.

Conquering these challenges will necessitate new data analysis and storage

A rapid drop in the cost of deoxyribonucleic acid (DNA) synthesis has rendered synthesis costs trivial for many laboratories. As described above, the testing phase remains a large bottleneck in production. Mechanical or electronic automation technologies cannot bridge the testing gap: the answers will have to come from biology itself (Rogers et al., 2015; Xiao et al., 2016) with the aid of computational models (Rogers and Church, 2016). Indeed, genetic sensors have now been developed which signal when the modified micro-organism has the sought-for phenotype and is making a desired product. This will enable the evaluation of millions of designs per cycle. However, it will also create an unprecedented amount of data. In the age of machine learning, ultimately the data should inform the next iteration of design without human intervention (Rogers and Church, 2016). For example, AutoBioCAD promises to design genetic circuits for *Escherichia coli (E. coli)* with virtually no human user input (Rodrigo and Jaramillo, 2013).

Box 3.1. **IT/computation convergence in bioproduction and a universal serial bus (USB) for biotechnology** *(cont.)*

Algorithms are needed that incorporate machine learning to correlate data from different data sets for the purpose of linking genes, proteins, and pathways without a priori knowledge (Wurtzel and Kutchan, 2016).

Many researchers have called for completely new computational languages for biotechnology. It is argued that variants of natural languages such as English are too imprecise and ambiguous to be useful in tackling the highly complex systems of biology and biotechnology. The time seems right for dedicated programming languages for the life sciences. Sadowski, Grant and Fell (2016) argue that the most crucial need is the development and adoption of high-level machine languages for executable bioprocesses. Antha is perhaps the first bona fide attempt to create a programming language for general-purpose computation in biology. It is built on Google's Go programming language, but incorporates domain-specific features. It is claimed to enable experiments of new levels of complexity.

Research and commercialisation bottlenecks in bioproduction

The commercial successes in metabolic engineering have been dwarfed by the research successes. In response to a lack of commercial success, researchers at the Korea Advanced Institute of Science and Technology (KAIST) have recently suggested ten general strategies of systems metabolic engineering to successfully develop industrial microbial strains (Lee and Kim, 2015). Systems metabolic engineering differs from conventional metabolic engineering by incorporating traditional metabolic engineering approaches along with tools of other fields, such as systems biology, synthetic biology, and molecular evolution. Many companies are competent in one or more of these specialisms, but few can integrate them all into a production process. In this and other fields of biotechnology there is a need for better collaboration between academia and industrial biotechnology companies (Pronk et al., 2015), and far more rapid transfer of knowledge between the public and private sectors.

At a more detailed level, the literature reveals key biotechnological challenges that need to be further addressed to improve the translation from the laboratory to the market. Box 3.2 describes the most frequently cited biotechnologies that need to be further developed. Co-ordinated targeted public research funding is particularly required in these areas.

Box 3.2. **Several biotechnologies need to be further developed to improve the translation from laboratory to market**

Frequently cited biotechnologies in need of further development include:

- **Biomass pre-treatment and consolidated bioprocessing (CBP).** The US Department of Energy endorsed the widespread view that CBP technology is the ultimate low-cost configuration for cellulose hydrolysis and fermentation (a process that makes cellulose accessible to microbes) (US DOE, 2006). In CBP a biocatalyst that makes a bio-based chemical is also responsible for releasing fermentable sugars from cellulosic biomass (such as wood or sugar cane), thereby removing an expensive dedicated enzyme step. This also reduces the number of reactors required in a bioprocess. There have been research successes (e.g. Salamanca-Cardona et al. [2016]), but as yet no viable commercial process.

Box 3.2. **Several biotechnologies need to be further developed to improve the translation from laboratory to market** *(cont.)*

- **Growth on Carbon1 compounds.** Progress has been slow because bacteria known to use C1 substrates can be difficult to work with in an industrial setting. Introduction of genetic carbon utilisation pathways from such bacterial strains into tractable production strains also presents significant challenges (Burk and van Dien, 2016). Nevertheless, many C1 compounds are available in large volumes (e.g. methanol) and others are greenhouse gases that can be harnessed (methane, carbon monoxide, CO_2). The low cost and ready availability of these molecules makes them attractive feedstocks for bioprocessing. LanzaTech, founded in New Zealand, has developed this technology to the point of large demonstration, and is due to build a fermentation plant at a Belgian steel works to convert highly toxic carbon monoxide and hydrogen into ethanol. This effort is partly industry funded, and partly funded through the European Union (EU) Horizon 2020 programme.
- **Computational enzyme design.** Current approaches to engineering enzymes for improved activity and specificity are semi-rational at best. Although the field is still in its infancy, computational enzyme design has the potential to facilitate rational protein engineering or even design completely novel functions (Privett et al., 2012). The frontier is in integrated computational/experimental metabolic engineering platforms to design, create, and optimise novel high-performance enzymes (Barton et al., 2015).
- **Minimal cells for bio-contained microbial factories.** The starting point for designing future production strains will be minimal, or chassis, cells (in other words, self-replicating minimal biological machines that can be tailored for the production of specific chemicals or fuels). Ostrov et al. (2016) have developed computational and experimental tools to rapidly design and prototype synthetic organisms. As much as the development of synthetic genomes has already been reported, the required effort is on a scale that has not yet been explored. Biocontainment to prevent the escape of genetically modified microbes into the environment remains another goal in using and developing industrial production strains. Currently there are necessary but insufficient metrics to evaluate biocontainment (Mandell et al., 2015), and therefore the design strategies are as yet incomplete.
- **Robustness.** Natural micro-organisms were not intended for the extreme conditions of industrial production, and new characteristics to make them more robust have to be engineered (Zhu et al., 2011). So pervasive is the issue that the United States' Defense Advanced Research Projects Agency (DARPA) has a research priority dedicated to it. DARPA's Biological Robustness in Complex Settings (BRICS) portfolio will consist of a set of programmes that aim to elucidate the design principles of engineering robust biological consortia and to apply this fundamental understanding towards specific applications such as on-demand bioproduction of novel drugs and fuels.
- **Productivity.** Most natural microbial processes are incompatible with an industrial process as the product titres (grammes per litre of product), yields (grammes of product per gramme of feedstock) and productivity (grammes per litre per hour) rates are often too low to be scalable (Maiti et al., 2016). A fundamental constraint on host cell productivity is the metabolic burdens that lead to undesirable physiological changes. Engineering cell metabolism for bioproduction not only consumes energy molecules such as Adenosine triphosphate (ATP), but also triggers energetic inefficiencies in the cell (Wu et al., 2016). Titre, yield and productivity may be perceived as issues for near-market R&D, but the challenges have been so pervasive and intractable that there is probably a need for more funding of basic research.

Box 3.2. **Several biotechnologies need to be further developed to improve the translation from laboratory to market** *(cont.)*

- **Small-scale fermentation models.** Fermenters – the enclosed and carefully controlled reactors where micro-organisms make useful products – are the ultimate arbiters of process optimisation. But they are costly to run and typically require expert supervision. Small-scale fermentation is also lacking in a number of areas, such as pH and aeration control and the ability to sample frequently. It is hoped that solutions will lie in microfluidics (Burk and van Dien, 2016). Microfluidics is the science and technology of manipulating and controlling fluids, in microscopic quantities (microlitres to picolitres), in exceedingly small channels. Being able to work with fluids in such small volumes means that the surface area-volume ratio is very large. This helps to speed reactions (heat transfer, mass transfer, gas transfer), and in the process of fermentation would also save on expensive media for growing microbes.
- **Gene and genome editing in production strains.** Targeted genome editing and engineering have until recently been laborious and costly. Efficient methods of enabling multiplex genome editing are urgently needed (Esvelt and Wang, 2013). Settling of patent issues around the genetic editing tool CRISPR/Cas9 (Ledford, 2016) would be helpful as this technology lends itself to work on genetic manipulation of traditional production strains like baker's yeast (Stovicek et al., 2015) and *E. coli* (Jiang et al., 2015) but also to non-conventional strains such as the model diatom *Phaeodactylum tricornutum* (Nymark et al., 2016) (diatoms are unicellular photosynthetic aquatic organisms).

Tax incentives for industrial R&D

Tax incentives reduce the marginal cost of R&D and innovation spending and are usually more technology neutral than direct support. Over the past decade, OECD countries have increasingly turned to tax incentives (rather than grants or other direct forms of support) to support investment in R&D (OECD, 2014a). The majority of OECD countries use such tax incentives, as do many of the BRICS (Brazil, Russia, India, China and South Africa) economies. In the United States, tax incentives are regarded as an important way to stimulate the bio-based materials industry. A range of such measures was suggested during the United States 112th Congress, with some measures reintroduced subsequently in the 113th Congress.

The existence of a production tax credit (PTC) in the United States covering bio-based products could promote investment, production, and adoption of bio-based products, much as existing biodiesel and cellulosic biofuels production tax credits have done for investment in those industries.

Technology clusters

Most OECD countries promote cluster-based programmes in supporting business innovation. Support for technologically specialised clusters exists in Australia, Belgium, Canada, Denmark, Ireland, Israel, the Netherlands, New Zealand, Poland, Spain, Switzerland, the United States and Singapore. The main rationale for public policies to promote technology clusters – through infrastructure, networking activities, training and other measures – is an increase in knowledge spillovers among actors in the clusters. This spill-over possibility is particularly relevant to industrial biotechnology as the research and production activities required are so diverse, from fermenter engineering to genetic engineering. An example of such a cluster in Europe is BioBased Delta, which has secured

the commitment of chemicals industry leaders such as Royal Cosun, Suiker Unie, Dow Chemicals, Cargill and Corbion (Deloitte, 2015).

Small and medium-sized enterprises (SME) and start-up support

All high-technology SMEs face challenges in their specific sectors. SMEs in biotechnology can face many years of high-risk research without revenues (Pisano, 2010), requiring expensive specialist facilities and complex market entry. Additionally, SMEs in bioproduction may have to compete with some of the world's largest oil and petrochemistry firms. Such large firms have proven markets, stable supply and value chains, proven technology and fully amortised production facilities. And yet governments place high expectations on SMEs.

Technology and regional clusters are a leading support mechanism for SMEs providing a range of services, such as: access to venture capital and other financial services; business advice on the strategic use of standards, labels, certificates, assistance with specific LCA and sustainability tools; and access to demonstration and testing facilities. National government programmes can provide a wide range of support mechanisms, especially exemptions from tax and national insurance payments.

Supporting local access to feedstocks

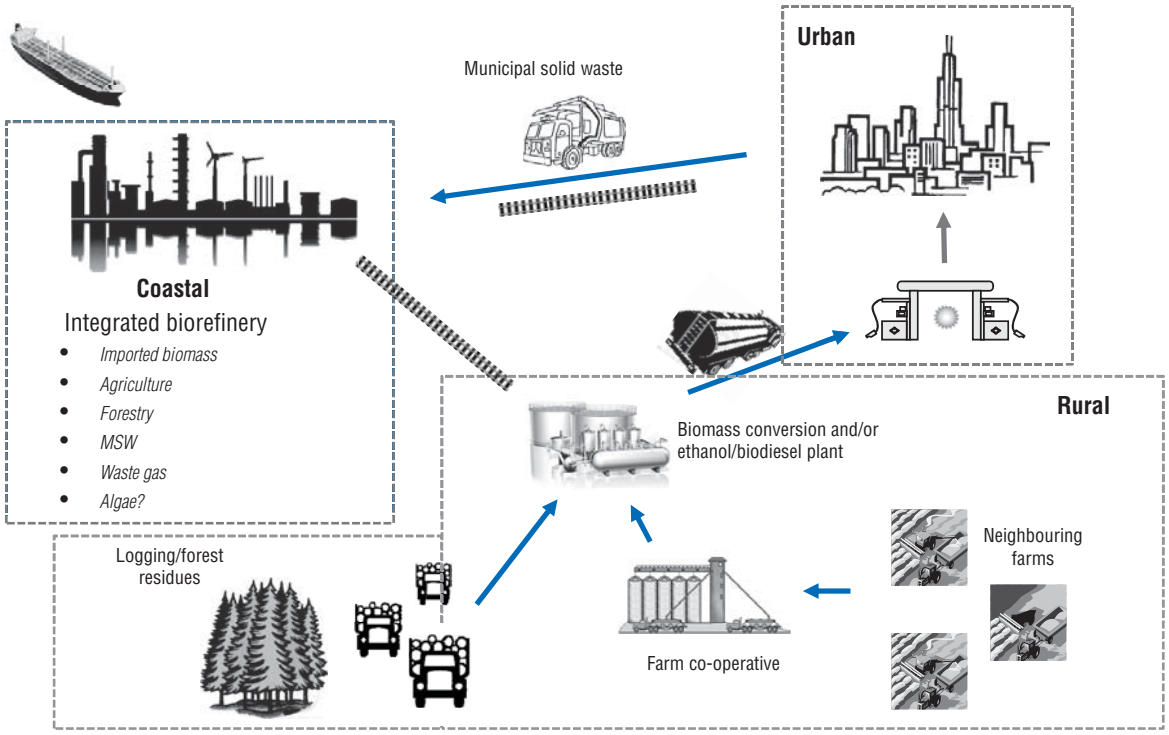
There are several policy advantages to making use of local feedstocks. First, using local feedstocks is more sustainable than transporting them from further afield or abroad (in terms of energy consumed in transportation). Second, creating local and rural jobs can serve objectives such as smart specialisation (OECD, 2013b) and knowledge-driven reindustrialisation. Nevertheless, there are major challenges ahead.

One major challenge is the complexity of biorefinery value chains (Figure 3.2). One aim of policy is to establish many interconnected local production plants that integrate with other nearby industries to ensure that residues and wastes are fully utilised in different processes (Luoma, Vanhanen and Tommila, 2011). Figure 3.2 is in fact an oversimplification, as it omits the contribution of research organisations and chemistry/biotechnology SMEs, and end-of-life strategies such as composting. Neither does the figure illustrate the cascading use of the biomass concept.[5] Nevertheless, Figure 3.2 does show the number of actors involved and the complexity of their interactions. For example, the biorefinery at Bazancourt-Pomacle in France (Schieb and Philp, 2014) involves 10 000 farmers.

Government programmes are promoting R&D across supply and value chains, but supply markets – e.g. for specialised production inputs – receive little attention (Knight, Pfeiffer and Scott, 2015), which can deter investors. This lack of attention to supply markets possibly reflects reluctance by governments to be seen to be intervening in markets and potentially contravening anti-competitive practices (Institute of Risk Management and Competition and Markets Authority, 2014).

The stakeholders concerned are so different that they almost never come into regular contact with each other in the fossil economy (for example, R&D centres and public research organisations tend not to be rural, and therefore need some mechanism to connect them to the other actors in the industrial biotechnology value chain). The stakeholder groups are also very diverse.[6] Consequently, there are roles to be played by policy to prevent the communication process from being random, ad hoc and inefficient. Analysis points to the potential importance of buyer co-operatives and other forms of supply market intermediaries (Knight, Pfeiffer and Scott, 2015).

Figure 3.2. **Generalised supply and value chains in biorefining**



Regional clusters can also be well positioned to evaluate regional development options. One factor in building capacity at the local level relates to the quality of local business networks, e.g. agricultural and forestry machine rings (equipment hire companies) and relationships of trust. Encouraging development of software-based decision support tools for local supply chain development would be a relatively low-cost public sector intervention.[7] European countries have frequently used the regional cluster mechanism to build capacity in industrial biotechnology.[8]

A successful cluster in France with tangible results and benefits is Industries & Agro-Ressources (IAR) in the Champagne-Ardenne and Picardy regions. With over 200 members, the IAR cluster unites stakeholders from research, education, industry and agriculture in France around the goal of optimising added value from the exploitation of biomass. It has regional roots, as it is a location where biorefining has been particularly successful. The IAR cluster also has a global mission of integrating external know-how through international strategic alliances. Performing a classic task of a regional cluster, the IAR assembles stakeholders from the whole value chain around a shared innovation problem.

International access to feedstocks: Biomass potential and sustainability

Large quantities of biomass are already being shipped around the globe, with most destined for OECD countries (BP-EBI, 2014). The use of biomass globally is increasing and will increase further (Schmitz et al., 2014). Biomass potential and its cost could become crucial factors that affect overall climate change mitigation costs (Rose et al., 2013).

A division is developing between advanced economies with little biomass to spare, such as in Europe, and developing economies not constrained by biomass shortages. This

calls for internationally harmonised policy to create and preserve sustainable biomass trade but also to prevent international biomass disputes (Bosch, van de Pol and Philp, 2015).

Box 3.3. **Examples of innovative approaches to feedstock supply: Japan and the United States**

The Biomass Nippon Strategy of 2002 was an early approach to supporting local access to feedstocks. Co-ordinated by three Japanese ministries – the Ministry of Agriculture, Forestry and Fisheries, the Ministry of the Environment and the Ministry of Economy, Trade and Industry – the strategy sets three types of goal: technical, regional and national. Objectives are set for production, collection and transportation, conversion technologies, and stimulation of demand for renewable energy or material use. The marketable opportunities for biomass technologies have been considerably strengthened.

The biomass town is an area where a comprehensive biomass utilisation system is established and operated through the co-operation of stakeholders in the area. Each step from biomass generation, conversion, distribution and use is linked among the stakeholders. Local governments lead the development and implementation of plans to create biomass towns. Approximately 300 biomass town plans have been developed in Japan since 2005. The Ministry of Agriculture, Forestry and Fisheries (MAFF) has also supported forming biomass town plans in pilot areas of four Association of Southeast Asian Nations (ASEAN) countries (Indonesia, Malaysia, Thailand and Vietnam).

For over a decade studies in the United States have examined the feasibility of acquiring 1 billion dry tonnes of biomass for the bioeconomy domestically. The first "Billion Ton Report" was completed in 2005 (US DOE, 2005), with updates in 2011 and 2016 (US DOE, 2011; US DOE 2016). The basics remain the same throughout these reports: that the United States, depending on assumptions made, may be able to produce 1 billion tonnes of dry biomass per annum, with the potential for significant substitution of fossil gasoline with renewable biofuels. The authors estimate that the United States currently uses 365 million dry tonnes of agricultural crops, forestry resources, and waste to generate biofuels, renewable chemicals, and other bio-based materials. The culmination of this work is an estimation that developing biomass resources and addressing current limitations to achieve a 1 billion tonne bioeconomy could expand direct bioeconomy revenue by a factor of five, contributing nearly USD 259 billion and 1.1 million jobs to the United States economy by 2030 (Rogers et al., 2017).

The stark reality of the current situation regarding biomass sustainability is that there are currently no comprehensive or standard definitions of sustainability, no ideal tools for measuring it, and no international agreement on the set of indicators to derive the data from which to make measurements. The metrics used to classify biofuel sustainability are still non-binding on biomass. However, major concerns exist over the sustainability of expanding the global bioeconomy, such as potential impacts on water and soil security, biodiversity, emissions and carbon footprint, net energy values, and land-use change, especially indirect land-use change (BR&D, 2016). Production of biomass needs policy to address these issues (Knudsen, Hermansen and Thostrup, 2015) along with the related development of standards. Genomics can also make large contributions to biomass sustainability, a fact which many governments fail to fully recognise.[9]

Production facility support: financing demonstration and full-scale biorefineries

Biorefineries at demonstration scale are difficult to finance because the volume of production is not large enough to influence a market price (Philp, Guy and Ritchie, 2013). Full-scale biorefineries are also difficult to build for reasons mostly relating to uncertainties of technology, supply and policy (BR&D, 2016). The private sector is unwilling to shoulder the entire financial burden of these large investments, and this has necessitated public-private partnerships (PPPs) to de-risk private investments. The largest such PPP currently in operation in Europe is the Bio-based Industries Joint Undertaking (BBI JU).

The demonstrator phase is a critical stage on the way to commercialisation. Larger than pilot scale, economic and technical limitations often make themselves evident during demonstration. Rather than having to correct these limitations at full-scale production, they can be corrected in a much less costly way at the demonstration scale.

The most common form of financing for such technologies in the United States is a hybrid of equity with either federal grants or federally backed loan guarantees (Box 3.4). A government loan guarantee is a promise by the government (the guarantor) to assume the debt obligation of a private borrower if that borrower defaults. Loan guarantees are similar to traditional project finance, but the government accepts the technology risk and backs the loan. This streamlines the approval steps and the control.

Box 3.4. **Loan guarantees and the US Department of Agriculture (USDA) Farm Bill, Program 9003**

For the Farm Bill of 2014, Program 9003, the USDA Biorefinery Assistance Program was renamed the Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program. The USDA was directed to ensure diversity in the types of projects approved and to cap the funds used for loan guarantees to promote bio-based product manufacturing at 15% of the total available mandatory funds. The important point to note, however, is that the same policy mechanism is now being used to support both biofuels and bio-based products and materials. It provides loan guarantees up to USD 250 million.

Funds may be used to fund the development, construction and retrofitting of:

- commercial-scale biorefineries using eligible technology
- bio-based product manufacturing facilities that use technologically new commercial-scale processing and manufacturing equipment to convert renewable chemicals and other bio-based outputs of biorefineries into end-user products on a commercial scale.

Refinancing, in certain circumstances, may be eligible.

Importantly, the programme makes a distinction between biorefineries, and bio-based manufacturing facilities. Federal participation (loan guarantee, plus other federal funding) cannot exceed 80% of total eligible project costs. The borrower and other principals involved in the project must make a significant equity contribution.

The InnovFin-EU Finance for Innovators was launched by the European Commission and the European Investment Bank (EIB) Group in the framework of Horizon 2020 to provide guarantees or direct loans to research and innovation projects. Among other project types, InnovFin finances industrial demonstration projects (Scarlat et al., 2015). This is a major step in Europe as loan guarantees had previously been missing from the portfolio of funding mechanisms for bioeconomy projects.

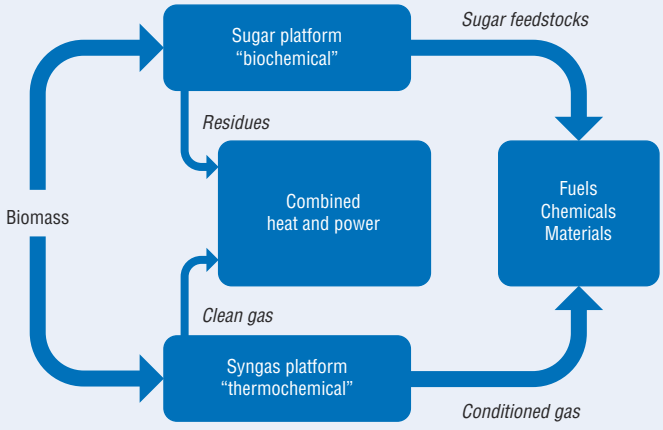
Governments should focus on integrated biorefineries

Overcoming feedstock and product price volatility may be best accomplished by making a range of fuels and chemicals at the same facility (Box 3.5). Such "integrated" biorefineries are technically very complex. The concept of an integrated biorefinery has become synonymous with the cellulosic biorefinery, of which there is a handful worldwide producing a trickle of cellulosic ethanol.

Box 3.5. **The concept of the integrated biorefinery**

An integrated biorefinery converts biomass to fuels, chemicals, materials and electricity (Keegan et al., 2013). Truly integrated biorefineries, which fully convert all the biomass, do not as yet exist, although some approach this level of conversion. At present, biorefineries are not set up for multiple feedstocks and multiple chemical products. Single-feedstock/single-product biorefineries are at economic risk owing to changes in feedstock price (especially for food crops). Having multiple feedstocks and products allows for operational changes when economic conditions require.

Figure 3.3. **Schematic representation of integrated biorefining**



There are particular advantages to the integrated biorefinery model. Integrated biorefineries afford the ability to switch between feedstocks and products when, for example, one feedstock is too expensive. Switching between feedstocks also helps cope with seasonal availability (Giuliano, Poloetto and Barletta, 2016). The economies of scale provided by a full-size biorefinery lower the processing costs of low-volume, high-value co-products. Common process elements are involved, lowering the need for equipment duplication, with subsequent decreases in capital cost. Co-production can provide process integration benefits (e.g. meeting process energy requirements with electricity and steam co-generated from process residues).

A summary of biorefinery types

There is a small number of biorefinery types (see Box 3.5 and Federal Government of Germany [2012]). First-generation biorefineries typically use a food crop of some sort as the feedstock. In terms of economic sustainability, Brazilian sugar cane is the favoured

feedstock for biorefineries at present (e.g. Government of the United Kingdom [2012]). As of 2011, there were 490 sugar cane ethanol plants and biodiesel plants in Brazil (Brazil Biotech Map, 2011), and around 300 such plants as of mid-2016.

Widespread concern over the use of food crops as feedstocks has driven the development of various types of second-generation biorefinery. The most important model is the biorefinery that uses lignocellulosic feedstocks for integrated biorefining of fuels, chemicals/materials and even bioenergy generated from residues. Lignocellulosic biomass can be grouped into four main categories (Tan, Yu and Shang, 2011): agricultural residues (e.g. corn stover and sugar cane bagasse); dedicated energy crops; wood residues (including sawmill and paper mill discards), and municipal paper and fermentable solid waste. Other emerging models of great potential are those in which waste industrial gases are fermented to make useful products. Once only conceptual, this type of biorefinery is becoming a reality but is far from common.

Biorefineries using wood as a feedstock are attracting more attention in the light of changes to world paper production patterns. Wood biorefining makes sense in many countries that have a long history of pulp and paper-making. The relatively high energy density of wood is attractive for transportation purposes. The most popular product lines are generally produced from wood fibres (biofuels, pulp/paper, bio-based materials and chemicals). However, the bark and other tree residues, like foliage, that constitute forest wastes remain an under-exploited resource (Devappa, Rakshit and Dekker, 2015). The most advanced wood biorefineries are found in Scandinavian countries.

Box 3.6. **Summary of an OECD survey of biorefinery types**

A survey was designed to be completed by biorefinery operators. Five operators replied and the respondents included the main biorefinery types:

- first generation (France) using food crops as feedstock (especially sugar beet, wheat and alfalfa)
- second generation (Norway) using wood as feedstock and producing ethanol and bio-based chemicals
- second generation (Italy) using lignocellulose (wheat straw, rice straw and giant cane [not sugar cane])
- second generation (Canada) using non-recyclable and non-compostable municipal solid waste
- second generation (Italy) using non-edible thistles as feedstock to produce bio-based chemicals.

Commonalities

With such a range of feedstocks and process technologies, there are many differences between these biorefineries. Nevertheless there are commonalities, among the most significant for the policy maker being that there is a local supply of biomass through arrangements with farmers, co-operatives, and cities (for municipal waste); all the biorefineries rely on proprietary technologies (none is using a licensed technology) even if partnerships have been involved; and, all receive some form of funding support from public authorities (at least for R&D and pilot projects).

Box 3.6. **Summary of an OECD survey of biorefinery types** *(cont.)*

Lessons to learn

- In a sector where the financial risks are very high, the principle "first mover takes all" does not apply: biorefinery types are evolving and feedstock/conversion technologies/products are diverse. The different feedstocks, technologies and business models can be attractive to a range of investors.
- Co-operative or family-owned business models seem to be a way to promote longer-term, risky projects.
- The issue of acceptability of biorefineries should not be difficult to overcome: some biorefineries have been in operation for 60 to 70 years in local communities.
- Local supply of biomass has to be implemented through special arrangements with local farmers, co-operatives, and cities. These arrangements will be essential to economic, environmental and social sustainability.
- Within integrated biorefineries, the business model makes low-value products (biofuel, ethanol, building block chemicals), a prerequisite for producing small volume speciality chemicals or ingredients for cosmetics, drugs and textiles of higher value.
- All of the biorefineries receive, or have received, some form of funding support from public authorities (at least for R&D and pilot projects). All have prospects for duplication of the biorefinery or licensing of their technology.
- Proof of the technologies should now allow a larger number of investors and operators to feel more secure about new projects. However, there will still be some dependence on oil and gas prices.
- The investments in the sample of biorefineries range from EUR 100 million to EUR 300 million. These amounts are significant but not large compared to oil refineries.

Impediments to future prospects

- The competitiveness of biorefineries is highly dependent on a level playing field between renewable biomass/feedstock and fossil fuels (see Philp [2015]).
- Public policies in Europe should be consistent over time. For example, there has been an issue of changing European policies regarding the fuel mandate and rate of incorporation of biofuel into transportation fuels. Investors fear government u-turns which can leave investments stranded.
- Uncertainties related to the volatility of global prices in domains such as energy (oil, gas, coal as competing feedstocks) and agricultural commodities make business plans for new projects extremely hazardous.

In conclusion, when contrasting the positive lessons learned from a sample of case studies of biorefineries and global challenges, it should be possible in the coming decades to remove hurdles and barriers and move much more quickly towards a bioeconomy as long as there is dialogue between actors (private, public, citizens). More case studies are needed along the way but the industrial bioeconomy has passed the stage of proof of concept.

Source: Schieb (2017), "OECD survey of biorefinery types".

For the future, marine biorefineries offer some important solutions, but also present technical challenges (Golberg and Liberzon, 2015). Perhaps the greatest benefit from using algae as both feedstock and biocatalyst is that this relieves pressure on land and food crops. Another advantage is that algae contain vast amounts of oil compared to terrestrial crops.

Market pull (demand-side policy measures)

Mandates and targets

Mandates and targets exemplify the different approaches to the introduction of biofuels in Europe and the United States. Incorporation targets (i.e. targets for the percentage of biofuels to be blended into gasoline and diesel) have been approved voluntarily by several EU member states as national initiatives (not an EU obligation). Biofuels policy in the United States has specified absolute production quantities through a mandate rather than a less-binding incorporation target (Ziolkowska et al., 2010). Mandates operate by the government setting a target volume for production for the private sector. Mandates and targets for biofuel production have become standard for the introduction of biofuels in OECD and BRICS countries (see OECD [2014b]).

Arguably the best-known mandate in bioproduction was created in the United States Energy Independence and Security Act (EISA) (2007) (Federal Register, 2010). This set high production volume mandates for biofuels. Together with blending mandates, a comprehensive policy support regime for biofuels has come into being in the United States.

However, if mandates do not distinguish among biofuels according to their feedstock or production methods, despite wide differences in environmental costs and benefits, governments could end up supporting a fuel that is more expensive than its corresponding petroleum product and with poorer environmental protection credentials (Global Subsidies Initiative, 2007). A key to preventing such a mistake in production support is, in the short term, harmonising LCA within the industry, and in the longer term developing robust and internationally coherent sustainability assessment.

Public procurement

Public procurement accounts for some 13% of gross domestic product (GDP) on average in OECD countries (OECD, 2012b). While possibilities exist to use public procurement to facilitate market entry for innovative bioeconomy products, challenges exist on both sides of the market.

On the supply side, only a small proportion of all bioeconomy products concern the business-to-consumer (B2C) market in which public procurers normally operate (e.g. fuel and consumer products). The largest share of bio-based products is chemicals and intermediates, which are only interesting to private industry in a business-to-business (B2B) market.

On the demand side, public procurement is a fragmented institutional landscape: in the European Union at the central governmental level only, more than 2 100 procuring authorities are listed. The total number of public procurers in the European Union (including regional and municipal level) is estimated at 250 000. This fragmentation inhibits co-ordination, and industry-specific knowledge and capacity building.

Moreover public procurers tend to be very price-sensitive, which is a barrier for any innovative product. Various governmental schemes address this issue. For example, the USDA BioPreferred Program specifically aims to increase the purchase and use of bio-based products, and has a catalogue of around 14 000 bio-based products. In the European Union, the 2014 legislation for innovative public procurement facilitates innovative solutions and the development of innovative products, but does not mention specific innovative products or product groups. However, projects like the Forum for Bio-Based Innovation in

Public Procurement (InnProBio) aim to enhance uptake of bio-based products in public procurement in Europe.

Standards and certification for bio-based products

Stringent standards and certification give confidence to consumers and industry as they provide credibility to claims of performance and sustainability (such as "bio-based", "renewable raw material", "biodegradable", "recyclable", or "reduced greenhouse gas impact"). Standards and certification help verify claims such as biodegradability and bio-based content that will promote market uptake (OECD, 2011b). Claims should be verifiable by consumers, waste management authorities and legislators. Third-party verification is a means to prevent unwarranted environmental claims.

Standards have strategic importance and provide a solid basis for introducing new products and technologies onto the market and a basis upon which further R&D can be built. They also help to remove the uncertainties that companies face. Standards are developed in close co-operation between industry, research and policy makers, which is essential to create the right environment for new products and technologies to grow to full-scale deployment.

Standards provide the necessary scientific basis for implementing legislation by demonstrating compliance with legal requirements. They can also be used to verify that policy goals and targets are being met.

To help to develop the market for bioplastics, the Japan BioPlastics Association (JBPA) started a certification programme for products containing biomass-based plastic. The association has established standards as well as a methodology for the analysis and the evaluation of these plastics. The programme includes a logo easily recognisable by consumers. The JBPA certification, called BiomassPla, specifies that products with the logo must contain 25% of bio-based plastic, and is calculated by weight.

Product labels should give clear and reliable information about the environmental performance of bio-based materials. This applies especially to bioplastics as these are the most likely to be contentious in society as a result of negative outcomes and perceptions coming from the use of petro-plastics. Today many different "eco-labels" are used globally, and definitions and certification procedures differ widely. Significant efficiency gains may be had from promoting a harmonisation of eco-labels in the medium term.

Fossil carbon taxes and emissions incentives

OECD analysis shows that the most cost-effective way to mitigate climate change is to gradually build up a global price signal on carbon through the use of market mechanisms (OECD, 2013a). The purpose of carbon pricing policy frameworks today should be to send clear and credible price signals that foster the low-carbon transition over the medium to long term (OECD, 2015a). Explicit carbon prices can either be set through a carbon tax, expressed as a fixed price per tonne of emissions, or through cap-and-trade systems, where an emissions reduction target is set through the issuance of a fixed number of permits, and the price is set in the market through supply and demand.

Once politically unpopular, the number of countries, states, regions and cities developing carbon price mechanisms now encompasses about 12% of global emissions, tripling coverage in a decade (Rydge, 2015). Fears that a carbon price will damage industrial competitiveness seem to be receding. Over 40 countries now have carbon pricing on energy.

However, carbon prices are often set very low. Around 90% of emissions from energy use are priced at less than EUR 30 per tonne (the low-end estimate of the cost of carbon), and 60% of emissions are subject to no price whatsoever.[10]

Governments can use carbon price revenues in a number of ways that should all be guided by efficiency. Perhaps the most appropriate use would be to finance the energy and manufacturing transition that climate change is necessitating. A proportion of the revenues could be used for R&D projects targeting the bioeconomy (e.g. Box 3.7).

Box 3.7. **Climate Change and Emissions Management Corporation (CCEMC) and CO_2 Solutions, Canada**

In April 2007, Alberta became the first jurisdiction in North America to pass climate change legislation requiring large emitters to reduce greenhouse gas (GHG) emissions. Two years later the CCEMC was created as a key part of Alberta's Climate Change Strategy and movement towards a stronger and more diverse lower-carbon economy.

The Government of Alberta administers the collection of all compliance funding each year and pools those funds in the Climate Change and Emissions Management Fund (CCEMF). The funds are sourced from industry and made available to the CCEMC through a grant from the Government of Alberta.

Alberta's Specified Gas Emitters Regulation identifies that facilities that emit more than 100 000 tonnes of CO_2-equivalent per year must reduce emission intensity by 12% below a baseline. Organisations that are unable to meet their targets have three compliance options: make facility improvements to reduce emissions below the required threshold; purchase Alberta-based carbon offset or performance credits; or pay CAD 15 into the CCEMF for every tonne they exceed the allocated limit.

The CCEMC manages its resources as a portfolio of projects with a wide spectrum of investments. The organisation funds projects at all levels of the innovation chain, with the bulk of its investment in projects at the demonstration and implementation phases.

For example, in 2012 and 2013, CO_2 Solutions (Quebec) secured CAD 5.2 million in grant funding from the Government of Canada's ecoENERGY Innovation Initiative and CCEMC towards a CAD 7.5 million project to optimise and pilot the technology for biological CO_2 capture from oil sands production (CCEMC, 2015).

The Government of Alberta outlined a plan in November 2015 for cutting the province's GHG emissions. The proposals included an end to coal-fired power generation as well as a carbon price of CAD 30 per tonne to 2018, rising in real terms after that. The plan has been backed by environmental groups and oil companies.

Fossil-fuel-subsidies reform

Not only do fossil-fuel subsidies undermine efforts to mitigate climate change, but they are also costly and distortive. By distorting costs and prices, fossil-fuel subsidies generate inefficiencies in the production and use of energy economy-wide (OECD, 2015b). Fossil-fuel subsidies differ in magnitude according to the method of calculation. The International Energy Agency (IEA) and the International Monetary Fund (IMF) use the price-gap approach, which is the difference between domestic fuel prices and a reference price, in this case international fuel prices. The IEA estimate differs year-on-year, but tends to be around half a trillion USD per annum. The differences between pre-tax and post-tax

estimates are very large.[11] According to an IMF estimate, fossil energy received a staggering USD 5.3 trillion, or 6.5% of global GDP, in post-tax subsidies in 2015 (IMF, 2015).[12] The IMF estimated that eliminating post-tax subsidies in 2015 could raise government revenue by USD 2.9 trillion (3.6% of global GDP), cut global CO_2 emissions by more than 20%, and cut premature air pollution deaths by more than half.

In the OECD countries over 550 fossil-fuel consumption subsidies have been identified (OECD, 2012a). These had an aggregate value of some USD 55 billion to USD 90 billion a year over the period 2005-11. Phasing out wasteful fossil-fuel consumption subsidies is politically difficult and unpopular, no matter how necessary (The Economist, 2014). The environmental and social costs of fossil-fuel subsidies (Whitley and van der Burg, 2015) are unlikely to be obvious to the public and may even be unclear to finance ministers (Edenhofer, 2015). But governments could use the money saved, among other things, to fund decarbonisation projects and technologies (Martin, 2016), such as those required by the bioeconomy.

Cross-cutting (mix of supply- and demand-side policy measures)

Developing metrics, and agreeing definitions and terminology

Robust data are needed to build metrics for the performance of a bioeconomy. The term "bioeconomy" itself means different things in different countries (Viaggi, 2016). A definition of "bio-based product" is needed as a standard for public procurement and business development. The debate over "waste or resource" (i.e. whether something is simply a waste material of no value or could be used as a productive resource) (House of Lords, 2014) is important for the bioeconomy. A mixture of terms and a lack of agreed definitions make it difficult to assess the volumes of different waste materials that can be used in biorefining. For example, gathering data on "agricultural residues" suffers from this definition problem. Such lack of clarity compares with the easily identifiable volumes available from crop feedstocks, such as sugar cane, where figures are collected internationally and are readily comparable.

As described in earlier sections of this chapter, a key objective of biorefining, especially for second-generation biofuels and bio-based materials, is the creation of value from waste (Fava et al., 2015). "Biowaste" is acquiring greater importance in biorefining, and tonnages should be known when formulating biorefinery roadmaps. However, any definition that excludes agricultural or forestry residues drastically changes available estimates. The definition of "waste disposal" could be changed to allow collection, transportation, and sorting in view of its possible conversion in biorefineries. Effectively, if a material is to be converted in a biorefinery, then it should no longer be regarded as a waste but as a resource.

Skills and education initiatives with industry for workforce training

The bioproduction industry and the bioeconomy generally pose challenges for higher education that need to be solved quickly. For example, a demand for 10 000 bio-based experts is expected in the next ten years in the Netherlands alone (Langeveld, Meesters and Breure, 2016).

For many, synthetic biology is a field of engineering, not of biology (Andrianantoandro et al., 2006). Synthetic biologists must be trained in one or several core disciplines: genetics, systems biology, microbiology, or chemistry. But they must also draw on engineering to be able to break down biological complexity and standardise it into parts, or to design new biological systems and components, drawing on the quantitative approach of engineering. Competence in engineering requires skills in mathematics, computing, and modelling (Delebecque and Philp, 2015). Multidisciplinarity is a recurring theme in industrial

biotechnology education. For example, to solve the complex problems associated with increasing the number of bio-based polymers, "researchers will need to work together across the conventional disciplines of agriculture, biology, biochemistry, catalysis, polymer chemistry, materials science, engineering, environmental impact assessment, economics and policy" (Zhu, Romain and Williams, 2016).

It is difficult for the young bio-based industry to find automation engineers specialising in high-throughput strain production. It has for a long time also been difficult to find fermentation staff. Perhaps hardest to find of all are employees well versed in experimental design and statistics (Sadowski, Grant and Fell, 2016). Addressing this issue is especially important now that dealing with large data sets is becoming more common. All such employees are necessary in bio-based production. The essential problem today is that skilled employees are not required in large numbers, because this is currently a small niche sector in manufacturing, so it is difficult for governments to prioritise education in these directions.

Scotland faces a series of challenges in maximising its development of industrial biotechnology, which includes skills shortages. In direct response to industry need, the Industrial Biotechnology Innovation Centre (IBioIC) has created bespoke educational programmes to meet this need across all educational levels: Modern Apprenticeships and Higher National Diplomas (HND) in industrial biotechnology, the United Kingdom's first collaborative Master of Science (MSc) in industrial biotechnology, and doctoral (PhD) studentships with universities across Scotland and industrial partners across the United Kingdom. IBioIC has been tasked with generating GBP 1 billion to GBP 1.5 billion of gross value-added (GVA) to the Scottish Economy by 2025 from the industrialisation of biology, and it requires a pipeline of talented people to deliver this. Here is the recognition of the need for a workforce, not just a research capability.

Including managerial and transferrable skills in curricula, and using massive open online courses (MOOCs)

The typical masters of business administration (MBA) programme is not suited to the biotechnology industry generally. The industry is typified by rapid change, and change management is an important issue. There have already been examples of short programmses for managers in industrial biotechnology that allow them to keep up with developments without leaving their post for long periods (e.g. a so-called "3-Day MBA"). In 2015, SynbiCITE in London ran a four-day MBA to cover the main strategies required to establish, build and manage a biotechnology company based around synthetic biology.

For decades there have been discussions about making research degrees more flexible (National Academy of Sciences, 1995), with the inclusion of training in transferrable skills. Today's researchers need skills relating to communication, problem solving, team work, networking and management know-how. The literature identifies several benefits of formal transferrable skills training (e.g. OECD [2012c]).

The traditional on-campus experience could be revolutionised by the explosion of MOOCs, which will enhance, if not partially replace, classroom and laboratory work. A specialist MOOC for industrial biotechnology is being offered jointly by the Technical University of Delft (Netherlands) and the University of Campinas (Brazil). It provides the insights and tools for the design of sustainable biotechnology processes. The basics of industrial biotechnology are used by students for the design of fermentation processes for the production of fuels, chemicals and foodstuffs. Throughout this course, students are challenged to design a biotechnological process and evaluate its performance and sustainability.

PPPs for creating and maintaining specialist training facilities

For early-career scientists, gaining access to bio-based production experience is difficult. Universities do not normally have the relevant facilities. An interesting training model is the National Institutes model in Ireland. One of these is a dedicated facility for training in bioprocessing (the National Institute for Bioprocessing Research and Training, NIBRT). For a relatively small country, Ireland has a large pharmaceuticals sector. The institute builds tailored training solutions for clients, ranging from operator through to senior management training, and training can be delivered in a realistic manufacturing environment. This type of environment is not one found typically in universities, and is more appropriate for the training of industry professionals. Such a facility could also be used to give students exposure to industry working conditions.

Another possibility is to offer placements in industrial research organisations such as Fraunhofer in Germany and VTT in Finland, or in research institutes like the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia, RIKEN in Japan and the Korea Research Institute of Bioscience & Biotechnology (KRIBB) and KAIST in Korea (Box 3.8). This allows opportunities to learn hands-on skills without attending to academic requirements such as publication in journals.

Box 3.8. **Research organisations and industrial biotechnology**

Several well-known research organisations offer services diversified from research in industrial biotechnology. These could prove pivotal in capacity building for national bioeconomies. A selection of these includes:

CSIRO, Australia. CSIRO works with a wide range of industries: agriculture and food; health and biosecurity; the digital, energy, land and water sectors; manufacturing; mineral resources; and oceans. Research is done in industrial and environmental biotechnology in the areas of: bioprocesses for sustainable resource management; biological catalysts for sustainable industries, and; understanding metabolic processes.

The organisation is working on using eucalyptus waste streams at timber or paper mills for manufacturing bio- polyethylene terephthalate (PET) bottles and packaging. These bio-based aromatic chemicals can be further converted to high-value derivatives to replace petroleum-derived additives in packaging materials. Expertise developed in biocatalysis and enzyme engineering is being extended to the development of synthetic biology capability. CSIRO has developed and patented an efficient enzyme nano-factory system, comprising several different nano-machine reactors that can convert glycerol into high-value molecules such as pharmaceuticals. CSIRO has also developed a technique for the production of graphene from soy bean oil (Seo et al., 2017).

RIKEN, Japan. RIKEN is the largest research organisation for basic and applied science in Japan. It combines basic research with a focus on innovation. The RIKEN Biomass Engineering Program combines several research areas, such as bioplastics, synthetic genomics, enzyme research, cellulose research, and cell factory research. It also has a business development office that promotes collaboration based on the needs of industry.[1] The RIKEN Junior Research Associate (JRA) programme provides part-time positions at RIKEN for young researchers enrolled in Japanese university PhD programmes. This gives PhD students the opportunity to carry out research alongside RIKEN scientists and also strengthens the relationships between RIKEN and universities in Japan.

Box 3.8. **Research organisations and industrial biotechnology** *(cont.)*

KRIBB, Korea. KRIBB has dedicated centres that respond to the needs of bio-based production at the Industrial Bio-materials Research Center; the Biochemicals and Synthetic Biology Research Center; the Cell Factory Research Center; and the Biotechnology Process Engineering Center. It also has an SME Support Center that supports capacity building and growth of bio-based SMEs.

KAIST, Korea. KAIST is a world-class centre for metabolic engineering with a strong focus on bioproduction of industrial platform chemicals and biopolymers (Lee et al., 2011). There are at least three centres at KAIST that contribute to work in industrial biotechnology: the Center for Systems and Synthetic Biotechnology; the BioProcess Engineering Research Center; and, the BioInformatics Research Center.

1. For example, the cell factory research team has biosynthesised 4-vinyl phenol, the monomer of a plastic with similar properties to polystyrene (Noda et al., 2015).

Poor regulatory policy can do harm

Regulation refers to the implementation of rules by public authorities and governmental bodies to influence the behaviours of private actors in the economy. The primary purpose of regulation in innovation policy should be to stimulate innovation, although the opposite effect is undeniably possible. Complex and time-consuming regulation is far more damaging to small bio-based companies than it is for large companies. Governments could act to reduce this impact.

A study for the government of the Netherlands (Sira Consulting, 2011) identified around 80 regulatory barriers to the bio-based economy. These were assigned different categories:

- **Fundamental constraints.** These call for a political and policy approach (e.g. import duties, level playing field, certification, and financial feasibility).
- **Conflicting constraints.** These barriers cannot be removed, but governments can help companies to meet the regulations (e.g. REACH regulations[13]).
- **Structural constraints.** These require adjustments to regulations, but do not demand policy or political action.
- **Operational constraints.** Here the regulation itself is not the problem but its implementation by e.g. local authorities is the problem. Especially for SMEs, these lead to substantial barriers to investment in the bioeconomy.

In the bioeconomy a frequently mentioned example of successful regulation to stimulate innovation is the single-use plastic bag ban in Italy (e.g. OECD, 2013c). In January 2011, Italy promoted a first-of-kind regulation aimed at replacing traditional plastic carrier bags with biodegradable and compostable bags (compliant with the harmonised CEN Standard 13432) and reusable long-life bags. This is considered to have triggered various desired effects in Italy including new investments in bioplastics production, with positive cascade effects along the value chain. The regulation created improvements in waste management, while Italian citizens adopted behaviour that has a positive impact on environmental sustainability.

Putting it all together: Systems innovation for a joined-up bioeconomy

Systems innovation is a horizontal policy approach to use combined technologies and social innovations to tackle problems that are systemic in nature. Systems innovation involves many actors outside of government (as well as different levels of governments)

and takes a long-term view. Therefore, in any systems innovation policy, governance is a key factor for success.

The bioeconomy automatically implies a need for systems innovation when the complexity of its supply and value chains is understood. For example, the production of transportation fuels is a system that goes from exploration and drilling through oilfields to vehicles and beyond. Such interconnected areas of policy action can be derailed by extraneous factors. An example of such complexity, and risk, comes from Sweden. Sweden has had the experience of trying to introduce ethanol as a transport fuel (Box 3.9), in a policy-driven effort to eliminate crude oil imports (Commission on Oil Independence, 2006), with the government's efforts being frustrated by various factors, including a lack of public acceptance (Sprei, 2013).

Box 3.9. **Sweden, ethanol, systems innovation and public acceptance**

To transition from petrol to ethanol requires flex-fuel vehicles that can use E85 fuel (85% ethanol/15% petrol). At first these were imported to Sweden. Ford introduced the first flex-fuel model in Sweden in 2002. From 2005 Saab and Volvo chose to enter the market. In the years that followed, the number of flex-fuel models continued to increase and by 2010 there were 74 models to choose from. Each year sales shares increased, in 2008 reaching almost 25% of the total market. But afterwards, sales dropped to 5% of new sold cars in 2011.

In the new system, the cars are part of the demand side, but a flex-fuel vehicle can also use straight petrol. Therefore it is necessary first to provide infrastructure to be able to purchase E85, and also to incentivise its purchase if it is more expensive than regular petrol. Ethanol (and alternative fuels) thus received considerable support from the Swedish authorities, from mandating an alternative fuel at fuel stations to subsidising sales of vehicles. The range of measures includes:

- a SEK 10 000 (over EUR 1 000) rebate for buyers of flex-fuel vehicles
- exemption from Stockholm congestion tax
- discounted insurance
- free parking spaces in most of the largest Swedish cities
- lower annual registration taxes
- a 20% tax reduction for flex-fuel company cars
- since 2005, Swedish fuel stations selling more than 3 million litres of fuel annually have been required to sell at least one type of biofuel (Swedish Parliament, 2009).

Fuels in Sweden are subject to both a carbon and an energy tax. Biofuels have, however, been exempt from these taxes to make them more price competitive and thus increase the uptake.

For private owners in April 2007 the rebate of SEK 10 000 was introduced for so-called "green" vehicles. Flex-fuel vehicles with petrol consumption below 9.2 litres per 100 kilometre (km) were included. The rebate was given until the end of June 2009. It was then replaced by a five-year exemption from the annual circulation tax. This tax is based on the CO_2 emissions of the vehicle, which thus varies from model to model. Part of the reduction in sales among private owners can be explained by the change in the rebate structure. However, the total sales of green vehicles have continued to increase, thus it seems that sales of conventional vehicles with emissions under 120 grammes of CO_2 per km have not been as affected by the change in rebate structure, especially new diesel vehicles (Sprei, 2013).

Box 3.9. **Sweden, ethanol, systems innovation and public acceptance** *(cont.)*

Many advantages were seen with the E85 fuel: it could reduce CO_2 emissions; it had the potential for national fuel production through wheat ethanol and lignocellulosic ethanol; and it provided the owner with an economic benefit when petrol prices increased. By the end of 2007, however, more negative voices started to be heard, questioning the environmental advantages of the fuel, and when food prices started to increase globally the connection to increased biofuel use was swiftly raised in public discourse, rightly or wrongly. Emissions connected to indirect land-use change and other production-related emissions were highlighted and weakened the image of ethanol as a green fuel. Public opinion started to turn against ethanol.

At the same time, diesel vehicles that met the criteria of being green started entering the market and offered a possibility to substitute for the flex-fuel vehicles. The price of E85 has not been low enough to compete with diesel, despite high subsidies. There were few compelling arguments left for choosing a flex-fuel vehicle compared to a low-emissions diesel vehicle. Subsidies may manage to create a market at first, but this cannot be sustained for a long time and there needs to be a more appealing policy in the long run.

A clear message is that systems innovation requires the co-ordinated efforts of several ministries or departments, including agriculture, trade, energy, environment, transport, and industry. This co-ordination is needed to limit wasteful duplication of work, and to prevent expensive policy lock-ins. A system breaks down if not all its parts are working. So it is with a systems approach to innovation policy.

The scope of bioproduction: The increasing diversity of products and expanding the scale of production

The goal of this part of the chapter is to introduce the reader to the growing range of bio-based products and to reflect on a number of policy and other implications of this growth.

Commodity products such as bioplastics that can be used for plastic bottles are high-volume, low-value products. Substituting petro-based plastics could achieve significant emissions savings. Biopharmaceuticals are very high value but are more difficult and expensive to bring to market. However, pharmaceuticals companies are already looking at sustainability in production processes (Watson, Cramption and Dillon, 2017), and bio-based production will be part of this. The specific example of synthetic spider silk, discussed below, is interesting due to the silk's very high strength and bio-compatibility, allowing it to enter a specialist market for artificial joints and tissues.

The day is foreseeable when light and medium transport can be electrified, thereby eliminating the need for liquid road transport fuels. As early as 2017, there has been a call in Scotland to consider a ban on petrol and diesel vehicles.[14] Scania of Sweden is introducing a hybrid truck for city use that can be driven electric-only or with renewable fuels. Indeed, it is a Swedish government ambition to have a fossil-independent vehicle fleet by 2030 (Hellsmark et al., 2016). For shipping and aviation, alternatives to liquid fuels are hard to envisage. But Los Angeles and Oslo are the first airports in the world that have incorporated biofuel into the regular refuelling process (Il Bioeconomista, 2016a). Several airlines are now purchasing bio-aviation fuel, including KLM and United Airlines. In May

2016, Cathay Pacific commenced a two-year programme of flights from Toulouse to China using renewable jet fuel. In September 2016, Gevo announced that it has entered into an agreement with Deutsche Lufthansa AG for the supply of up to 8 million gallons per year of alcohol-to-jet fuel (ATJ).

The high standard of living attained in OECD countries is not imaginable without the vast number of chemicals in everyday use. As 96% of all manufactured goods contain at least one chemical (Milken Institute, 2013), it is clear that petrochemicals will be much harder to replace than fossil fuels. The chemicals sector is the largest industrial energy user, accounting for about 10% of global final energy use (Broeren, Saygin and Patel, 2014). The chemicals sector represents the third largest industrial source of emissions after the iron and steel and cement sectors (IEA, 2012).

Approximately 8% of world oil production is used in plastics manufacture: 4% as raw material for plastics and 3-4% as energy for manufacture (Hopewell, Dvorak and Kosior, 2009). Therefore, by mid-century, crude oil consumption to make plastics could increase to 28% to 32% of today's levels of production of crude oil, which would put plastics in competition with fuels for crude oil use. Such growth is completely out of step with new oil discoveries, which are at their lowest in 60 years.

The most compelling route to drop-in (exact equivalent) or same-function (different molecule that has the same function) sustainable chemicals is through using renewable feedstocks. The idea of biotechnological routes to entirely unnatural chemicals only took hold with the emergence of metabolic engineering in the 1990s (Wong, 2016). Despite many challenges, there are several advantages to a biotechnological route compared to a strictly chemical route. Microbial metabolism is extremely diverse, and therefore there are very large numbers of biochemical reactions to choose from (one database contains 130 000 hypothetical enzymatic reactions). Microbial processes occur at low temperatures and mostly at ambient pressures, therefore making the biotechnological route attractive in environmental and economic terms.

To date renewable chemistry remains far ahead of industrial biotechnology in the production of commodity chemicals. Many chemicals have been produced to date using micro-organisms. Most of these remain as research successes. Many may never reach commercialisation. There are technical and financial reasons for this, and the two are interlinked (i.e. more efficient biotechnologies would bring down production price and make bio-based chemicals and materials more cost-competitive with petrochemistry). Fundamentally, bio-based production without public policy support faces a mountainous challenge given the economies of scale that exist in petrochemistry.

However, taking a closer look at what constitutes the modern petrochemicals industry, a relatively small number of chemicals represent a large proportion of total organic chemicals production. US DOE (2004) identified 12 building block chemicals that can be produced from sugars via biological or chemical conversions (building block chemicals are molecules with multiple functional groups that possess the potential to be transformed into new families of useful molecules). Saygin et al. (2014) estimated that a total of seven polymers could technically replace half of total polymers production in 2007. The significance of this is that it reflects how plastics have become the material of choice in a vast number of applications.

One significant development has been the arrival of bio-based equivalents of the thermoplastics that dominate the market: polyethylene (PE), polypropylene (PP) and PET.

Bio-PE and bio-PP are produced chemically from monomers which are produced by fermentation. They have identical performance characteristics to the petro-based equivalents and, importantly, can directly enter existing recycling systems. They can be categorised as bioplastics as their carbon content comes from renewable resources, and they therefore have a potential contribution to make to GHG emissions savings. It has been predicted that the global trend in bioplastics production will change significantly, coming to be dominated by durable bio-based thermoplastics (OECD, 2013c), rather than biodegradable plastics.

Biotechnological routes to producing aromatics (chemicals which give off an aroma) are particularly challenging. The aromatics are very high-volume chemicals with a large range of functions that cannot easily be replaced. Benzene production alone will amount to tens of millions of tonnes in 2017. Benzene has specific uses in its own right, but has very valuable value chains linked to other more valuable chemicals. However, commodity aromatics have proven extremely challenging to manufacture via bioproduction. There have been several studies focused on microbial aromatics production from biomass (Kawaguchi et al., 2016), but not aimed at commodity aromatics.

On the other hand, there are clear environmental drivers for producing bio-based aromatics (Eriksson, 2013). The largest renewable reservoirs of aromatic materials are lignin and hemicellulose. Lignin creates the greatest challenges for renewable sources of aromatics, but it is not a resource that can be ignored. There are about 50 million tonnes of lignin available worldwide per annum from pulping processes alone. The total lignin availability in the biosphere exceeds 300 billion tonnes and annually increases by around 20 billion tonnes (Smolarski, 2012).

Anellotech of the United States is one company with renewable chemistry solutions to the aromatics challenge. In their process, non-food biomass such as wood, sawdust, corn stover and sugar cane bagasse is rapidly heated, and the resulting gases are immediately converted into hydrocarbons by a proprietary, reusable catalyst. The resulting mixture of benzene, toluene and xylenes (bio-BTX) is identical to the petroleum-derived counterparts.

The BTX compounds are integral to the production of a wide range of plastics including polyurethane, polycarbonate, polystyrene and nylon. Aromatics are also widely used in the automotive industry, and the Toyota Group has championed the use of renewables in vehicles (OECD, 2011b).

Bio-based production and its visibility

For the public and policy makers, visible bio-based production has been lacking. In Table 3.3 the selected examples show that in the last few years this visibility has increased dramatically. Nevertheless, this revolution in production could remain unrecognised because a bio-based product looks identical to a fossil fuel-based equivalent (whether e.g. a tyre, smart phone screen or drinks bottle). Certification and labelling would help to improve visibility, giving confidence to manufacturers and helping with public perception and acceptance. The increased political impetus from 2015 onwards, especially COP21 and the drive towards a circular economy, could be used as levers to increase this visibility.

Table 3.2. **Bio-based products are becoming more familiar**

Product	Background
Latex from dandelions	Prototype tyres containing bio-based latex were showcased in December 2009 at the UN Climate Change Conference in Copenhagen. The Fraunhofer Society and the tyre company Continental have built a pilot plant to produce rubber from dandelions. The Russian dandelion thrives in soils unsuitable for agriculture.
Bottles from sugar	Both the Coca Cola and PepsiCo companies have plastic bottles that are at least partly bio-based. The Coca Cola bottle contains mono-ethylene glycol derived from fermentation of sugar. It is mixed with other components to make bio-polyethylene terephthalate (bio-PET). The long-term aim is to replace petro-based PET.
Graphene from soybean oil	Graphene is more than 200 times stronger than steel, and conducts electricity better than copper. About 1% of graphene mixed into plastics could turn plastics into electrical conductors. Graphene is, however, expensive compared to other materials. Researchers at CSIRO, Australia, have created a new method of graphene synthesis from soybean oil (Seo et al., 2017).
Castor nuts to wall plugs	DuPont extracts a chemical building block from castor oil from which is made a 68% bio-based polyamide (the synthetic polyamides are known as nylons). The polyamide is as strong as the nylon normally used to make wall plugs.
Bioplastics in cars	One of the earliest uses of bioplastics was in replacing metal or petro-plastics components in vehicles, saving greenhouse gas emissions and/or weight. Among others, Ford and Toyota are investigating and using bioplastics for uses such as textile car interiors. Daimler and Royal DSM worked together to create an engine cover that is a 70% bio-based plastic.
Sugar to carpets	Dupont and Mohawk combine bio-based propanediol and a petrochemical building block to make a carpet fibre that is soft, durable and easy to clean. The textile is 37% bio-based.
Yeast to face creams	Korres grows yeast cultures which produce hexapeptides (short peptides of six amino acids) when treated with ozone or irradiated with ultraviolet (UV) light. The compounds are added as anti-ageing active ingredients in face creams.
Biopharmaceuticals	Antibiotics have been traditionally produced from microbes. Synthetic biology has been used to manufacture a potent anti-malarial drug. Sanofi delivered the first large-scale batches of anti-malarial treatments manufactured with a new semi-synthetic artemisinin derivative to malaria endemic countries in Africa in 2014.
Nutrition and food/feed supplements	Cargill makes a sweetener using a synthetic biology yeast to convert sugar molecules to mimic the properties of stevia, with no need for the plant itself. Calysta specialises in the production of microbial proteins for the commercial fish feed and livestock markets.
Enzymes in detergents	Biological detergents contain a range of enzymes that allow washing to be done at lower temperatures, such as 30°C, thus saving energy, emissions and money.
Spider silk to medical implants	Spider silk is an exceptionally strong material. Silk material is now also being used for sutures, scaffolds, grafts and some medical implants. Oxford Biomaterials, Orthox Ltd and Neorotex Ltd are investigating a range of biomedical applications of genetically engineered spider silk. The United States army is testing protective garments for soldiers made from spider silk. An *E. coli* variant of spider silk could replace Kevlar in air bags.

Concluding remarks

This chapter demonstrates the beginning of the transition to a new model of bio-based production (Il Bioeconomista, 2016b). Several countries are strong in bioeconomy research and relatively poor in deployment (via biorefineries and chemical production plants). However, the cellulosic biorefineries, upon which great hopes are pinned, are proving worryingly susceptible to technical failure. To date, the volumes of cellulosic ethanol production are small, and still dependent on government support (Peplow, 2014). Research progress is far ahead of full-scale deployment, which is not a surprise in such a young industry. This chapter points to the major policy needs to redress the balance between R&D and commercial success.

Schieb et al. (2015) forecast that, in order to make the industrial bioeconomy a success, the number of biorefineries, both in the United States and Europe, would have to be increased to between 300 and 400. That represents a very large investment, most of which will need to come from the private sector. In many engagements with the bio-based private

sector the most consistent message is that policies have to be stable and long term so that the private sector has the confidence to invest in risky projects.

The sustainability messages are reaching the fossil industry. Change is evident when the Rockefeller Family Fund trustees say: "While the global community works to eliminate the use of fossil fuels, it makes little sense – financially or ethically – to continue holding investments in these companies" (Cunningham, 2016). Even Saudi Arabia plans to diversify its economy and end its reliance on oil in the near future.[15] The oil industry must also be aware of the potential of electric vehicles to disrupt its business. About 2 million barrels a day of oil demand could be displaced by electric vehicles by 2025, equivalent in size to the oversupply that triggered the biggest oil industry downturn in a generation, which has occurred over the past three years (Bloomberg, 2017).

The biggest stimulus may now come with the ratification of the Paris Agreement in 2016. There is a concentration of effort in policy circles on carbon pricing, and this has the potential to raise large revenues for governments. It remains, then, for policy makers to spend their new bounty on technologies to decarbonise energy and production. This chapter has suggested a number of areas in science and technology where such resources could be channelled. It is essential that the bioeconomy be part of future energy and production landscapes (Szarka et al., 2017).

Notes

1. To date, synthetic biology is covered by the regulations that pertain to genetically modified organisms (GMOs). There is probably no need for major modification to the system already in place in the medium term, but a watching brief is required from governments. Biosafety issues appear to be the same between GMOs and synthetic biology, except that the multidisciplinary nature of synthetic biology means that there is a need for greater awareness and training for stakeholders not familiar with the field. However, synthetic biology raises specific biosecurity concerns:
2. With synthetic biology, DNA can be readily designed in one location, constructed in a second location and delivered to a third. The use of the finished genetic material can therefore be de-coupled from its origins.
3. Synthesis might provide a route to those seeking to obtain specific pathogens for the purpose of causing harm, thereby circumnavigating national or international approaches to biosecurity (at present, however, genetically modifying a pre-existing pathogen is much easier than using synthetic biology to create a pathogen).
4. It is widely agreed that there is a need for a screening process for synthetic DNA manufacture and sale. The main aspects that deserve consideration for control are: screening to avoid synthesis of known pathogens or toxin-related DNA; screening to avoid shipment to dubious customers; and licensing of equipment and substances required for the synthesis of oligonucleotides.
5. In the cascading use concept, high-value, low-volume products are made from biomass, then higher-volume, lower value products until most value has been extracted. At this point residues may be used to generate electricity, hot water or district heating.
6. Regional stakeholders include farmers, foresters and their trade associations and co-operatives, buyers, agricultural and forestry machine rings, hauliers and other logistics professionals, chemicals and fuels companies, biorefiners, venture capitalists, food companies, R&D organisations, technology SMEs, waste management companies, regulators, recycling and waste management organisations.
7. For example, a database developed by Black et al. (2016) for the assessment of biomass supply chains for biorefinery development covers origin, logistics, technical and policy aspects. Improved decision making is assuming greater importance as the need to establish bespoke biomass supply chains becomes a reality. Industrial developers will face many business-critical decisions on the sourcing of biomass and the location of biorefineries. Software of the type described could simplify decision making. It could be developed in an open-source manner with regional cluster organisations.

8. This has happened e.g. in Belgium, France, Germany, Italy, the Netherlands, and the United Kingdom, all countries with large and strategic chemicals sectors. In 2006 the German Federal Ministry of Research and Education initiated a cluster competition to strengthen industrial biotechnology in Germany. Five industrial biotechnology clusters were selected and received funding a total of EUR 60 million.
9. While not widely recognised, genomics has started to revolutionise food production without genetic modification. Advances are being made in using genomics in breeding programmes to speed success across a wide range of crops and animals. Production of most animals and crops can benefit from genomics. This includes some critical economic considerations, such as feed efficiency and disease resistance, which can benefit food security now and into the future. Genomics can also make large contributions to biomass sustainability. For example, energy crops will be part of the future of biomass production, and the impact of genomics in plant breeding is in its infancy. This message is not well understood in many policy circles. Many governments need to better understand the advantages of genomics in agriculture, and could more efficiently steer relevant research programmes, e.g. by sponsoring programmes that train farmers in genomics (the Irish Beef Data and Genomics Programme is a good example).
10. The "carbon pricing gap", a synthetic indicator showing the extent to which effective carbon rates fall short of pricing emissions at EUR 30 per tonne, sheds light on potential ways of strengthening carbon pricing (OECD, 2016).
11. Pre-tax subsidies exist when energy consumers pay prices that are below the costs incurred in supply.
12. Post-tax consumer subsidies arise when the price paid by consumers is below the supply cost of energy plus an appropriate "corrective" tax that reflects the environmental damage associated with energy consumption and an additional consumption tax applied to all consumption goods for raising revenues.
13. Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) is a European Union regulation dated 18 December 2006. REACH addresses the production and use of chemical substances, and their potential impacts on both human health and the environment.
14. See *www.thetimes.co.uk/edition/scotland/energy-experts-call-for-ban-on-diesel-and-petrol-vehicles-jfghn0qdz*.
15. See *http://vision2030.gov.sa/en/media-center*.

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PART I

Chapter 4

Tapping nanotechnology's potential to shape the next production revolution

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Nanotechnology is a general-purpose technology (GPT), which enabled numerous product and process innovations, as well as productivity and sustainability enhancements in nearly all existing market sectors. Nanotechnology has the potential to enable further innovations and establish new market sectors in the near future. Continuing advancement of nanotechnology requires substantial investment in research and development (R&D) and commercialisation. Investment should be supported by inter- and intra-national collaborations, providing virtual research infrastructures, which allow the sharing of otherwise prohibitively expensive equipment and foster interdisciplinary research ecosystems that are inclusive of academia, governmental research and large and small companies, in order to fully harness nanotechnology's innovation power in all existing and in potentially new industry sectors. Novel business and innovation-funding models should be developed, which account for the increasing multidisciplinarity and the advancing digitalisation of innovation. Regulatory hurdles to the commercialisation of nanotechnology should be removed.

Introduction

Nanotechnology is increasingly used in production processes and manufactured products. For example, nanotechnology enables 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). Nanotechnology can also underpin cheap single-use products (such as lab-on-a-chip diagnostics).

Expectations that nanotechnology could play a larger role in the productive sector, and in science, are based on the view that nanoscience, and its application in nanotechnology, represent the ultimate breakthrough in controlling matter on a length-scale where the shape and size of assemblies of individual atoms determines the properties and functionalities of all materials and systems, including those of living matter.

In the short and medium term, nanotechnology will continue to improve existing products and production processes. Entirely new products and processes from nanotechnology-based innovations may arise in the long term. In both cases, productivity could increase, and demand for skilled workers will rise. Greater understanding of nanometre-scale phenomena will be needed, requiring investments in basic and applied science.

In order to achieve the economic and societal benefits that nanotechnology could enable, policy makers should consider implementation of some specific policies. This chapter discusses and suggests the following policies:

- investment in research and development (R&D) and commercialisation of nanotechnology
- support of and investment in virtual research infrastructures, which allow the sharing of otherwise prohibitively expensive R&D equipment and foster a collaborative research environment that is inclusive of academia, governmental research and large and small companies
- fostering of interdisciplinary research ecosystems
- support of novel business and innovation-funding models, which need to take account of the increasingly collaborative nature of R&D for complex inventions, as well as the advancing digitalisation of research and production processes
- recognition and timely removal of regulatory barriers to innovation in nanotechnology, including regulatory uncertainties.

From scientific curiosity to disruptive technology

The term "nano" describes a length-scale (i.e. 1 x 10^{-9} m to 100 x 10^{-9} m. A standard sheet of paper is about 100 000 nanometres thick). "Nanotechnology" is a collective term for all technological effects and material properties that are enabled by scientific phenomena occurring at the length-scale of a billionth of a metre. Interactions at this so-called

"nanoscale" are of key importance to life and the material world. The nanoscale is the realm where individual atoms, which do not have any material properties in their own right, form bonds with other atoms. This creates the smallest (nanoscale) functional units of materials, whose properties, functionalities and processes can be observed in the inorganic and biological world around us.

The widest definition of nanotechnology therefore includes all phenomena and processes occurring at this length-scale, spanning a broad range of developments from quantum-effect computing (in the discipline of physics), to invisible materials (in solid state chemistry), to artificial tissue and biomimetic solar cells (in biology), to theranostic actuators used in medicine (enabled by the nano-electro-mechanical systems created in the engineering disciplines).

Through the ability to understand and design material properties at the atomic scale, nanotechnology is a key enabler of many advanced production processes and manufactured products. For example, 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). Nanotechnology provides the technical solution that makes flexible computer screens possible. And nanotechnology can underpin new advanced single-use products (such as lab-on-a-chip diagnostics).

Nanotechnology is a general-purpose technology (GPT) (Helpman, 1998; Lipsey, Carlaw and Bekar, 2005). It has often been predicted that nanotechnology could initiate the next industrial revolution. Nanotechnology is expected to have a significant (in some cases, disruptive) impact in all existing industrial sectors, and to harbour the ability to enable the creation of entirely new sectors. As it develops, nanotechnology will enter a widening range of uses and require complementary technologies and institutions.

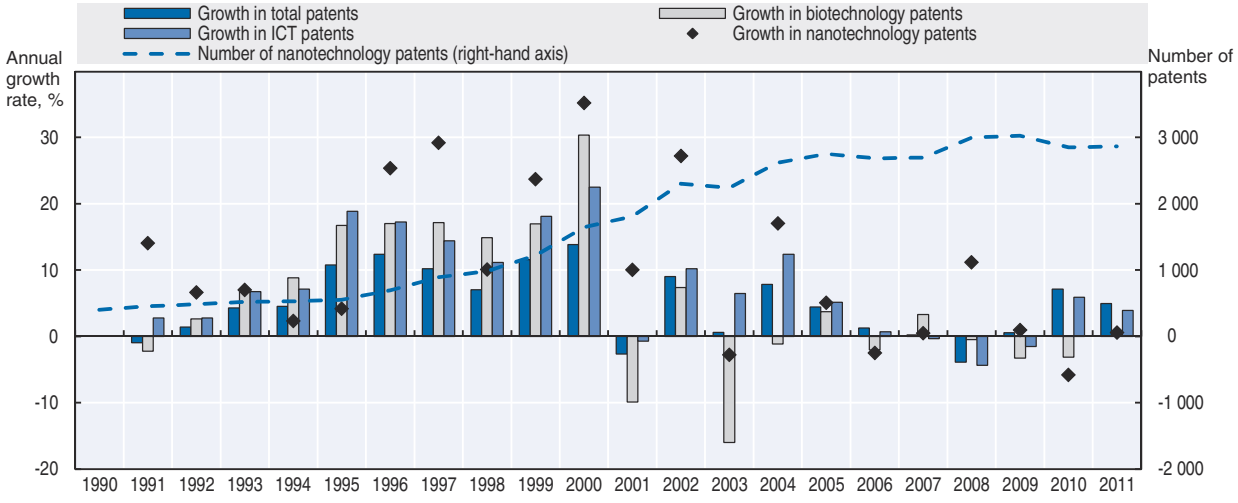
In the 1980s, science- and technology-foresight studies envisaged rapid advancements from the initial discovery of material control on the nanometre scale, to the ultimate creation of any complex functional system from its smallest building blocks (Drexler, 1986).

Figure 4.1 shows repeated episodes of growth in the number of nanotechnology patents (black diamonds), several times larger than observed for comparable enabling technologies, such as biotechnology (grey bars) and information and communication technology (ICTs) (light blue bars). Together with the overall increase in the number of nanotechnology patents filed between 1990 and 2011 (dashed blue line, right hand axis) the figure illustrates that the diverse field of nanotechnology repeatedly spurred a hype-like approach to research and technology patenting. Figure 4.2 provides more detail on the sub-areas of nanotechnology that have given rise to an increased interest in specific nanoscale-based phenomena.

Figure 4.2 illustrates the wide range of nanotechnology applications for which patent protection has been sought. The figure also shows change over time in the nine nanotechnology sub-areas assigned by patent offices for classification purposes. While "nano-optics" and "information processing, storage and transmission" were the dominant nanotechnology sub-areas in 1990, "nano-composites" and "manufacture or treatment of nano-structures" were the largest sub-areas in 2011. The percentages displayed in Figure 4.2 are based on the counts of filings in IP5 patent families, according to earliest filing date.

Figure 4.1. **Evolution of patents in nanotechnology, biotechnology and ICT, 1990-2011**

Annual growth rates, IP5 patent families

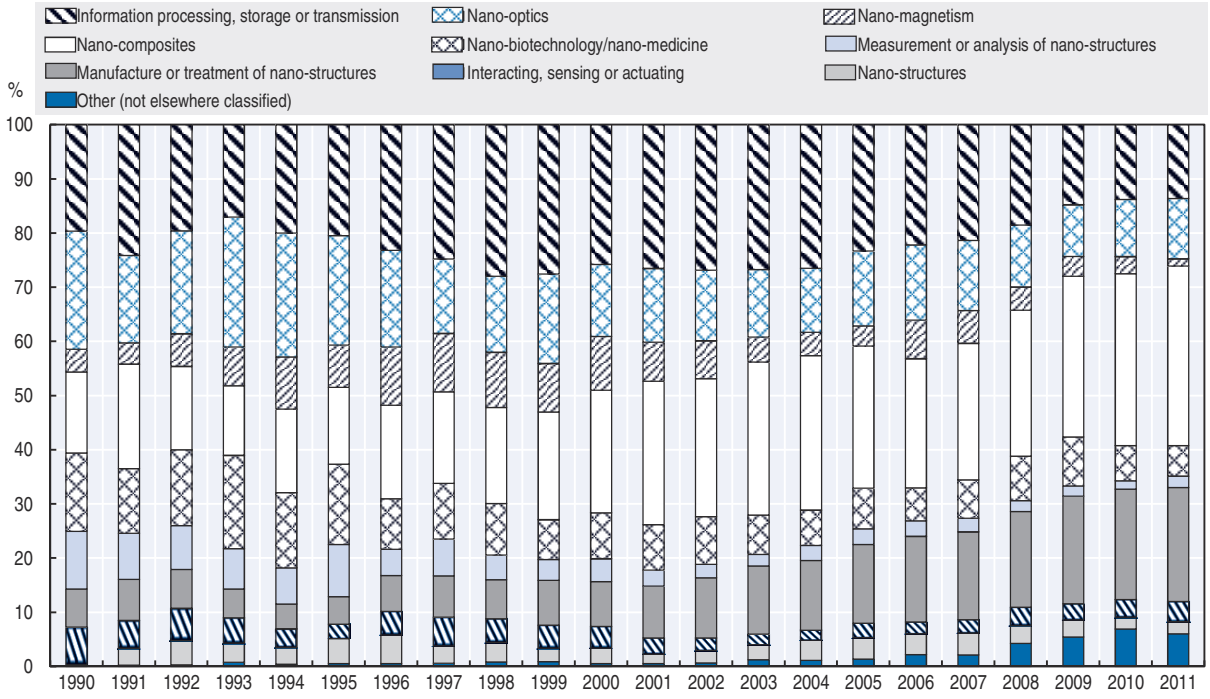


Source: OECD (2016b), *STI Micro-data Lab: Intellectual property* database, *http://oe.cd/ipstats* (accessed October 2016).

StatLink http://dx.doi.org/10.1787/888933473820

Figure 4.2. **Development of nanotechnology sub-areas, 1990-2011**

Share of sub-areas in nanotechnology patents, IP5 patent families



Note: n.e.c. = not elsewhere classified.

Source: OECD (2016b), *STI Micro-data Lab: Intellectual property* database, *http://oe.cd/ipstats* (accessed October 2016).

StatLink http://dx.doi.org/10.1787/888933473830

The changing face of a revolutionary enabling technology

The first prediction of the innovation potential of nanotechnology is often attributed to the physicist Richard Feynman, who, in a 1959 lecture "There's plenty of room at the

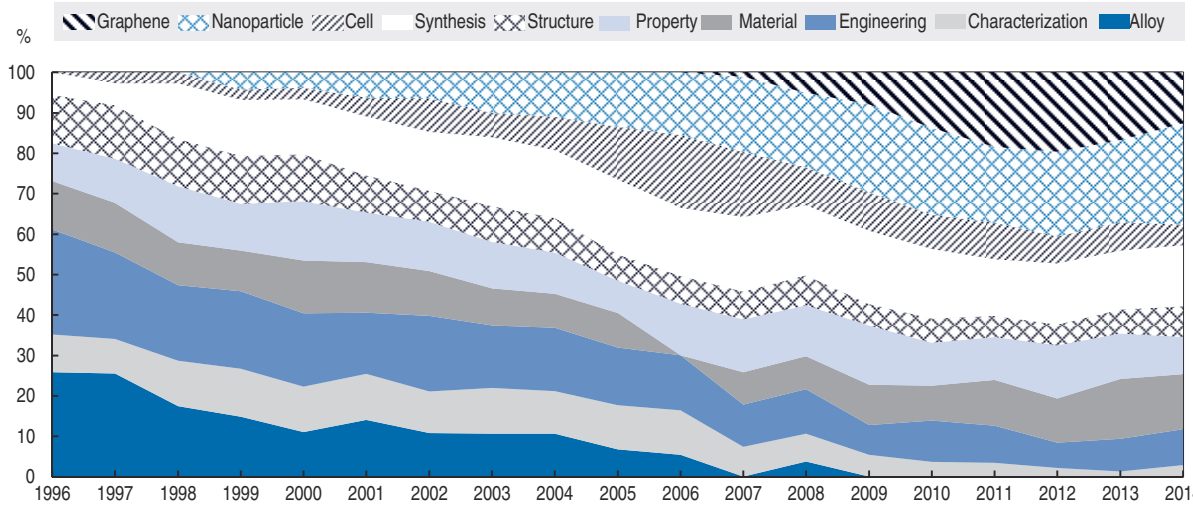
bottom", delivered a vision of the power to revolutionise all material sciences and technologies that would come from controlling matter on the nanometre scale (Feynman, 1960). But it was not until the development of advanced microscopy in the 1980s, and above all the invention in 1981 of the Scanning Tunnelling Microscope (STM) (which enabled real-time visualisation of the nanoscale) (Binning and Rohrer, 1986), that the term nanotechnology was coined. From then on the term was used increasingly to describe a rapidly growing interdisciplinary research area.

Research at the nanometre scale, however, is subject to thematic shifts, driven by new understanding of the nanoscale as well as other scientific breakthroughs, such as the isolation and characterisation of graphene in 2004 (Novoselov, 2004).

Figure 4.3 illustrates the changes of the ten most often appearing keywords in titles of papers in nanotechnology scientific journals between 1996 and 2014. The figure shows that over the last 20 years the main focus of nanotechnology research has shifted from being a predominantly engineering-oriented discipline concerned with inorganic materials and their properties in 1996 to a more widely applied scientific discipline. In 2014, the field of nanotechnology was predominantly concerned with specific applied materials, such as nanoparticles and graphene, and the application of nanotechnology included biological tissue, such as the cell. The percentages displayed in Figure 4.3, are based on standardised counts of occurrences of the ten most often used keywords in the titles of scientific papers, published in nanotechnology journals.

Figure 4.3. **Changing citation of the most important keywords in nanoscience literature (1996-2014)**

Share of the ten most important nanotechnology keywords in scientific literature



Source: Elsevier (2016), *Scopus Custom Data*, database, Version 12.2015 (accessed October 2016). Text mining performed with VOSviewer, version 6.1.3.

StatLink http://dx.doi.org/10.1787/888933473842

As the enabling aspect of nanotechnology develops further, the technology will enter a widening range of uses and require complementary technologies and institutions, such as those that foster interdisciplinary research and those that provide access to the powerful characterisation equipment needed for nanotechnology research.

Until now, however, developing an understanding of nanoscale phenomena and applying this understanding in advanced materials design and nanoscale engineering processes have proceeded much more slowly than was expected in the 1980s. The main causes for the disappointing pace of progress have been the high cost of R&D instrumentation, as well as nanotechnology's notorious failure at the stage where laboratory-scale procedures need to be scaled up and commercialised. The main hurdle to achieving commercial-scale production has been insufficient understanding of physical and chemical processes at the nanometre scale, and the inability to control production parameters at that scale. However, in recent years progress has been made in solving this problem, especially because advanced data storage and processing techniques are increasingly used in material design and development processes.

Whereas expectations of numerous new nanotechnology-enabled products were initially unfulfilled, nanotechnology-enabled innovations have gradually improved established production, manufacturing, maintenance and transport processes. Over the last ten years, R&D on, and adoption of, nanotechnology-based processes and products has increased rapidly. For example, many large companies adopted nanotechnologies as enablers to process innovations in order to reach environmental and sustainability goals (e.g. cutting carbon emissions through the lowering of reaction times in chemical production processes; increasing the fuel efficiency of their vehicle fleets by adding combustion-enhancing nanoparticles to diesel fuel; reducing the use of organic solvents by working with nanoparticles that can be suspended in water; and replacing known toxins and carcinogens in high-performance composites, such as the replacement of nickel powder in alloys for turbine blades).

The application of nanotechnology in large-scale product innovation manifested itself not as a disruptive technology, but as a step-wise improvement of known materials. An example of this is in the cosmetics sector, where large particles of zinc oxide were used in cosmetic sun-blockers, giving the cream a thick, opaque consistency. Nanotechnology was employed for the high-accuracy manufacture of only those nanometre-sized zinc oxide particles that show the highest absorption of (and thus protection against) ultraviolet (UV) light. This ultimately enabled the addition of translucent sun-block UV protection into everyday cosmetics. With regard to other applications, a 2014 report found that nanotechnology could contribute to sustainability and resource efficiency in the tyre industry, for example (OECD, 2014).

In addition, advanced nanomaterials are increasingly used in large-scale manufacturing processes for high-tech products. An example is the use of nanomaterials (mainly colloidal synthetic amorphous silica) for finely abrading and polishing electronic and optical components.

According to a study by the European Commission (EC, 2012), an estimated 70% of product innovation is based on materials with new or improved properties. Future production and manufacturing of materials and components will be increasingly digitally controlled, with sensor-based links between the so-called "digital twins" (i.e. the all-virtual design of complex objects, which runs parallel to their development in the material world, see Chapter 6) and the material world driving feedback and improvement loops based on machine learning, as discussed in the following section.

The link between the digital and the material worlds

One of the most important medium and long-term uses of nanotechnology is in developing high-accuracy sensors and detectors. Based on the ability to probe individual atomic and molecular material building blocks, nanotechnology-enabled sensors can be made with a variety of purposes. For example, such sensors can be tailor-made to: detect organic molecules in ambient air with high sensitivity and selectivity (as is required in air safety monitoring systems); provide the results of rapid screening tests (such as those required in blood analyses during influenza epidemics); conduct online quality control during high-throughput manufacturing processes in complex systems (such as those required to produce computer chips); and, test the structure and selected properties of newly designed and developed materials (such as those created during the novel high-throughput process of concurrent design described in Chapter 6).

The role of nanotechnology as the link between the digital and physical worlds will become increasingly important, as the use of digital twins becomes increasingly widespread. For small and medium-sized enterprises (SMEs) to adopt the use of digital twins, however, the cost of this technique must be significantly decreased. The concept of "mirror worlds", created by the computer scientist David Gelernter over two decades ago, has most recently been enabled by faster Internet connections, data storage, cloud computing and advanced algorithms, which allow big data on a material's or a component's performance to be stored in huge "data lakes", ready to be used in subsequent design, development or maintenance processes (The Economist, 2016). The McKinsey Global Institute estimates that linking the physical and the digital worlds could create up to USD 11 trillion in economic value annually by 2025, with one-third of that value being created in manufacturing (McKinsey Global Institute, 2015).

Large materials and engineering companies are increasingly utilising the versatile sensor capabilities of nanotechnology to create digital twins of every category of physical asset they develop (The Economist, 2016).

Nanotechnology's driving role in the next production revolution

Today, nanotechnology provides innovative solutions to a number of major challenges ranging from the environmental sustainability of industrial processes (e.g. through reduction of the use of energy and solvents) to the mitigation of climate change (e.g. through nanotechnology-based carbon-capture and energy-storage materials) to the affordable provision of products with preventative health benefits (e.g. through the creation of invisible sun-blockers) to the development of rapid diagnosis kits (e.g. through small-scale sensors for lab-on-a-chip applications). Three industrial cases are presented here – in solar cells, the automotive industry and plastic bottle making – to highlight the effects that nanotechnology is having, and could have, on industrial processes and technologies, with a focus on productivity.

Case study A: Solar cells will become safer and more widespread through nanotechnology

Nanotechnology is set to revolutionise the nature and manufacture of solar cells in four ways:

1. Through careful design of the composition and/or the structure of a material on the nanometre scale, new photoactive materials have been created that outperform incumbent materials in at least three ways:
   - **Production cost.** The production cost of common solar cells can be significantly decreased by replacing expensive metals (such as platinum) with cheap nanocomposite materials (such as combinations of zinc oxide nanowires on flexible sheets of graphite) (MIT, 2012), or honeycomb-like structures of graphene interspaced with lithium carbonate (Michigan Technological University, 2013).
   - **Environmental safety.** The environmental safety of solar cells can be improved by replacing known toxic materials (such as lead and cadmium) with nanocomposites of little or no safety concern (Los Alamos National Laboratory, 2013).
   - **Energy efficiency.** The energy efficiency of common solar cells can be increased by reducing the thickness of photoactive material layers in solar cells to the bare minimum (i.e. to a double layer single-molecule thick sheet of graphene and other materials), thus allowing the stacking of several such cells in a single element (MIT, 2013).
2. Reducing the size of photoactive materials to the nanometre scale significantly broadened the range of industrial processes suitable for the production of solar cells, ultimately enabling the manufacturing of solar cells to shift from an energy-intensive highly specialised zone-melting process (for traditional silicon solar cells) to low-cost large-scale thin-film deposition techniques (from liquid and/or gas) and high-throughput printing techniques (e.g. screen-printing, roll-to-roll printing). The latter techniques are applied in the production of novel, so-called second- and third-generation, solar cells.
3. Thin-film solar cells furthermore enable the creation of flexible and/or spherical solar cells. This enhances collection efficiency compared to flat cells (Lin et al., 2014). Engineers at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, have developed thin-film solar panels, manufactured at relatively low cost, which are flexible to the point of being able to be draped.
4. Shrinking all active components of a solar cell (i.e. the photoactive material and both electrodes) to the nanometre scale also allows the unobtrusive incorporation of near-transparent solar cells into a wide range of building components. This could enhance overall power generation from currently unused sunlight.

While the rapid advancement of solar cell technologies and the boom in the solar cell market have so far only been marginally related to nanotechnology, the technology's four-fold impact on the production of solar cells will have effects in the medium and long-term future.

At the moment, the most widely used solar cells are so-called first-generation solar cells (made of crystalline silicon) and second-generation solar cells (made of thin films of metals, which are often toxic). In the medium term, third-generation solar cells made of organic dyes will increasingly enter the solar cell market. Nanotechnology-based innovations enable both the functionality of these cells and their low-cost production process. In addition, second-generation solar cells will be improved by nanotechnology through replacement of their toxic components with nanocomposites of similar performance but fewer or no safety concerns.

In the long term, nanotechnology-enabled translucent solar cell technology and advanced printing processes will allow building components to be covered with low-cost solar cells. This could significantly increase the share of global energy consumption coming from solar, which currently stands at 1% (IEA, 2014).

Case study B: The automotive industry and its consumers benefit from nanotechnology-enhanced products and processes

The automotive and transport industries greatly benefit from nanotechnology owing to these industries' rapid innovation cycles. Numerous applications have been successfully commercialised. For example, fuel efficiency and environmental performance have been improved by advanced nanomaterial-based catalysts and fuel additives; carbon black nanomaterials are enhancing the performance of tyres; and car bodies have been enriched with nanotechnology-based anti-corrosion protection.

Nanotechnology-based innovations are also revolutionising complex automotive manufacturing processes. For example, to increase the fuel efficiency and corrosion resistance of vehicles, a growing number of metal-based automotive body panels have been replaced with polymer composites. This improvement, however, has come at a cost to manufacturers and the environment, because the polymers are not electrically conductive. This meant having to exclude the new body parts from the electrostatic paint line hitherto used in production. Vehicle manufacturers now had to coat the polymer-based body parts with a conductive primer in a separate step, before the part could be painted together with the metallic parts (or manufacturers had to establish a second paint line for the polymer-based parts, often resulting in different properties and optical appearance). A solution to this problem is introduced by nanotechnology: the addition of small amounts of carbon nanofibres (i.e. extremely long, thin and light fibres consisting of carbon) to the polymer composite renders the latter electrically conductive, while no other relevant properties are affected (Burton, 2006). It was estimated that this innovation could reduce manufacturing costs by USD 100 per vehicle, with a net value to the automotive industry globally in the order of USD 2 billion annually (Burton, 2006).

Case study C: Nanomaterials radically reduce the cost and CO_2 footprint of polyethylene terephthalate (PET) bottle production

The food processing industry is notoriously shy to adopt drastically new technologies and materials, given the heavy regulatory burden surrounding innovations in food, feed and food contact materials, as well as the increasingly sceptical and nostalgic attitudes of consumers, which affect opinions on food and nutrition more than any other consumer product. Nevertheless, it was the food processing industry that experienced one of the first and most rapid nanotechnology-based process innovations. In 2007, a patent was filed to protect the idea of including heat-absorbing nanoparticles into the freshly soft-blown plastic polymer drink bottle, in order to shorten the time necessary to harden the bottle under infrared light. In this process, titanium nitride nanoparticles act as absorbers of infrared light, thus becoming local miniature heat sources within the polymer (US DOE, 2011; Guler et al., 2013). Less than 12 months later, the European Food Safety Authority (EFSA) had reviewed and approved the safety of these nanoparticles in typical plastic drink bottles, which are made of the plastic PET (EFSA, 2008). This innovation is today sold all over the world as a concentrated solution of the nanoparticles that simply needs to be added to the PET melt at the preform injection stage. The innovation is used by some of the largest PET bottling companies.

The productivity enhancement achieved by this innovation is claimed to significantly lower manufacturing costs. The cost reduction comes from a shortening of the curing time of the hot-blown PET bottle, as well as a 38% reduction of energy use during the process, which can be translated to almost double the cost savings and twice the CO_2 reduction associated with any alternative polymer additive.

Implications for public policy

High R&D costs may be offset by virtual infrastructures

Significant investment is needed in R&D. Such investment can help to build research communities and to generate sufficient knowledge until the technology has matured and can support itself through industrial applications and commercialisation. Nanotechnology research is capital intensive, requiring clean-room facilities and advanced microscopy techniques during most steps of the R&D procedure. The R&D cost of nanotechnology will remain very high (for example, in the United Kingdom the use of a state-of-the-art microscope for one day might cost over GBP 5 000) and might even rise with advancing specialisation: increasingly specialised and powerful equipment, such as combined nano-fabrication (manipulation) and characterisation (imaging) devices must be used to fully understand processes and properties on the nanometre scale.

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 within one region. Consequently, nanotechnology requires increased efforts in inter-institutional and/or international collaboration to advance to its full potential. Publicly funded R&D programmes should allow the involvement of academia and industry (i.e. both large and small companies) from other countries. Doing this enables targeted solution-driven collaborations between the most suited partners and creates a virtual R&D infrastructure (i.e. a network of institutes and laboratories that possess complementary instruments and expertise, between which researchers can move as if they were working in a single research facility). An example of such an R&D infrastructure is the European Commission's QualityNano project (QualityNano, 2015).

The creation of virtual infrastructures that connect existing elements of R&D infrastructure in interdisciplinary networks of scientists and engineers offers a cost-saving alternative to financing multiple nanotechnology R&D centres. In addition, long-distance remote access to high-tech R&D equipment is being enabled by increasing digitalisation, such that users of state-of-the-art microscopes can even conduct their experiments from a computer terminal located on another continent.

Interdisciplinarity must be supported and encouraged

Nanotechnology tends to thrive at the interface of traditional disciplines. This is where discipline-specific research and engineering infrastructures are available – favouring multidisciplinarity – and the expert knowledge in traditional disciplines is pooled. Examples of such conducive environments include virtual networks, such as Germany has created to support biomedical nanotechnology (Malsch, 2005), and research institutes such as the United Kingdom's Interdisciplinary Research Collaborations. Policy makers should seek to support multidisciplinary networks, ideally providing an R&D infrastructure. Such networks should include academia and large and small companies. Public-private-partnerships should be encouraged to foster both scientific excellence and business skills.

As a general-purpose technology (GPT), nanotechnology has an impact on a wide range of industry sectors. Policy instruments that optimally foster nanotechnology therefore need to be designed in a way that takes into account the multidisciplinary

approaches that the technology can require. In 2008, most OECD countries had specific policies and dedicated R&D funding instruments in place, and approximately half of those countries had established new organisational and institutional frameworks to support nanotechnology (OECD, 2008).[1]

New business and innovation-funding models are required to enable the next production revolution

The relatively high cost of nanotechnology R&D hampers the involvement and success of small companies in nanotechnology innovation. As a result, nanotechnology R&D is mainly conducted by larger companies. Large companies are better placed to assimilate nanotechnology due to their critical mass in R&D and production, their ability to acquire and operate expensive instrumentation, and their ability to access and use external knowledge (OECD, 2010). Policy makers should foster innovation and commercialisation in small companies, by providing sufficient and appropriate incentives and support for these companies to fulfil their innovation potential. Policy makers could seek to improve SMEs' access to equipment by: increasing the amount of money SMEs receive in research grants; subsidising/waiving the service fee; or providing SMEs with vouchers for equipment use. The development of networks that involve academia, public research laboratories and large and small companies creates an environment in which a research infrastructure can be shared, while simultaneously helping start-ups to establish themselves within a current or potential commercial value chain.

For future high-throughput R&D processes (such as concurrent design and digital twins described in Chapter 6) to become widely used in the nanotechnology community, decision makers in the public and private sector should consider reviewing existing business and funding models. New models may be required, because both the R&D for new and converging technologies, as well as the invention and manufacture of products enabled by these technologies, differ from traditionally observed processes (e.g. car manufacturing, food processing and steel production). Specific challenges in arriving at an adequate ecosystem may arise from the following issues:

- The ubiquitous use of concurrent design and digital twins requires the establishment of and open access to large databases that store basic R&D data (and metadata) from academic research laboratories, large industry R&D and SMEs (typically start-up and spin-out companies). A first challenge arises from questions of how the establishment of such databases should be funded, who should be responsible for the creation and maintenance of such databases, and how quality control should be governed. While it seems most appropriate that these responsibilities should fall to an international collaboration among public authorities, it is still unclear how development, maintenance and quality control costs should be covered. Public authorities should collaborate on the development of a strategy and roadmap for an internationally shared data commons.
- Policy makers also need to find a model under which pre-competitive data can be openly shared without compromising the ability of universities and small businesses to raise income. In situations where large firms, SMEs and academia were to make their basic R&D data (i.e. both product and process parameters and specifications) available in an openly accessible database (i.e. a data commons), it would be difficult (perhaps impossible) to draw up licensing deals or use agreements to benefit the upstream knowledge contributors (i.e. the scientific researchers). This lack of protection of data on basic R&D would undermine current models of collaboration between universities and industries,

such as the funding of doctorate programmes on specific research topics, which are based on the assigned ownership of different parts of the knowledge needed in the collaboration (e.g. background intellectual property [IP], peer-reviewed papers and materials metadata). Public-private collaboration agreements of this kind are typically negotiated and secured under collaboration contracts in which each party's research capacity, skills and background IP are assets that determine the party's share of ownership of the resulting invention. If a university's main bargaining asset (consisting of data on basic R&D) were to be made freely available, academia may miss out on funding from industry collaborations, and subsequently be set back by not being able to afford the purchase of state-of-the-art-equipment needed for nanotechnology R&D.

- Decision makers and policy makers should work on the creation of an innovation ecosystem that allows the pre-competitive sharing of basic R&D data without compromising the protection of IP created by those that cannot currently afford patent protection. Adequate ecosystems may be based on making patenting more affordable for SMEs, but they may also entail the protection of IP by other means.
- The concept of the digital twin increasingly emphasises the importance of computational algorithms that can turn large amounts of materials data and process data into models and simulations of inventions. If the digital twin was to become a dominant innovation tool in a value chain, value-added would shift from the R&D expert to the computing and machine-learning power of the algorithm. For example, in the value chain of turbine blade material manufacturing, the most important knowledge is currently held by materials and processing experts. These experts suggest incremental innovations to the existing materials mixture and/or the processes used to make the turbine materials and the turbine blade. In a world of digital twins, the innovative turbine blade would be developed using a digital model of itself, by continuously feeding basic R&D data on turbine blades into a machine-learning algorithm, which simulates the ideal materials components and processing parameters of a turbine blade, while continuously measuring the targeted parameters of a prototype turbine blade, and adjusting parameter settings in case of deviations. In this futuristic scenario, the computer algorithm would provide the most important innovative step. In this connection consideration should be given to the international harmonisation of IP protection for computer programmes and software, which are currently treated differently under US and EU law.

Regulatory uncertainties must be eliminated in internationally collaborative approaches

Regulatory uncertainties regarding risk assessment and approval of nanotechnology-enabled products severely hamper the commercialisation of nano-technological innovation. This is because products awaiting market entry are sometimes shelved for years before a regulatory decision is made. In some cases, this has caused the closure of promising nanotechnology start-ups, while large companies have terminated R&D projects and innovative products. A 2016 OECD report investigated the treatment of some nanotechnology-enabled products in the waste stream, concluding that more needs to be done to safely integrate nanotechnology in its diverse uses (OECD, 2016a). Policies should support the development of transparent and timely guidelines for assessing the risk of nanotechnology-enabled products, while also striving for international harmonisation. Since 2006, the OECD has led international efforts to harmonise regulatory approaches to the safety of nanotechnology-enabled products (OECD, 2011).

Note

1. An ongoing OECD study aims to find out if such early specific funding programmes for nanotechnology R&D have since been replaced by more generic policies.

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The Next Production Revolution
Implications for Governments and Business
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PART I

Chapter 5

3D printing and its environmental implications

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This chapter examines the potential environmental sustainability implications of 3D printing (also called "additive manufacturing") as it displaces other manufacturing technologies, and lists top priorities for policy interventions to improve environmental sustainability. It considers several of the most widely used 3D printing technologies as they are today and describes trends related to 3D printing's ability to supplant other technologies in the near future as this method evolves. This analysis compares the environmental impact of today's typical 3D printing with two classic manufacturing methods, citing life-cycle assessments, scoring greenhouse gas emissions and other air pollutants, material toxicity, resource depletion, and other factors. It also explores how 3D printing will expand into more industries. While this chapter mostly concerns plastic processes, other materials such as metal are also considered. While widespread 3D printing would not automatically be an environmental benefit as practised today, technologies already exist that, if brought from the industry's fringes to its status quo, could dramatically shift manufacturing towards more sustainable production. Since the industry is at a crossroads, well-placed incentives today might establish beneficial technologies for decades to come, to make widespread 3D printing an important part of a more sustainable future.

Introduction

Additive manufacturing (hereafter 3D printing) has the potential to dramatically shift industrial manufacturing methods away from traditional technologies and democratise the production of manufactured goods. If scaled up across multiple industries in the next decade 3D printing also poses potential benefits and drawbacks for environmental sustainability. 3D printing groups together many different technologies and processes that use a digital file to build a physical 3D object by successively adding layers of material until the model is complete. As with other forms of manufacturing, 3D printing is largely a way of producing parts; most products are assemblies of many parts, only some of which can be 3D printed.

Traditional manufacturing methods being replaced by 3D printing are too numerous and varied to describe thoroughly; this chapter will only consider machining and injection-moulding. Machining begins with a block of material and cuts some away to produce the final shape. It can use a wide variety of materials, including plastics and metals, to produce high-precision parts with a fine surface finish. Modern machining is often computer-controlled and begins with the same type of digital file as that used by 3D printers. It does not require mould tooling, so each part produced can be unique, though it often requires skilled labour and generates significant material waste. Injection-moulding melts plastic and injects it into the cavity of a pre-existing mould, forming the part in seconds. The two halves of the mould then separate to allow part removal and reunite for production of the next part. Injection-moulding can use any thermoplastic, and can produce high-precision parts with a fine surface finish. Due to the mould tooling required, it generally cannot produce custom parts, but can produce thousands or millions of the same part at low cost and with little material waste.

Although 3D printing has gained recent traction in manufacturing and among the general public, the method is older than most of us realise, having been first developed in the 1980s. Widespread public awareness took hold in the early 2000s due to the expiration of early patents, which enabled low-cost desktop printing via the open-source movement. The industry as a whole is expanding rapidly thanks to the falling of printer and materials prices, rising print quality and the convergence of open-source and private innovation (Hornick and Roland, 2013).

The rapid growth of the industry has been called a “gold rush”. This characterisation is corroborated by the doubling in the number of 3D printers sold between 2005 and 2011 (McKinsey, 2012). Sales are projected to exceed USD 10 billion per year by 2021 (Wohlers, 2014). Currently, the majority of 3D printing produces prototypes, models and tooling; only 15% directly produces parts in sold goods (Beyer, 2014). This trend is changing as the manufacturing segment of the industry is growing at 60% per year (Cohen, Sargeant and Somers, 2014). 3D printed goods are sold in high-value, small-run niches such as aerospace, jewellery and medical devices. Almost no full products are 3D printed, but commercial products contain 3D printed parts.

Many proselytise on 3D printing's sustainability, but few understand its true impact: much of its praise is unfounded, while much of its long-term promise is overlooked. In 2009, the US National Science Foundation convened 65 experts to write the Roadmap for Additive Manufacturing (RAM), which included a section on sustainability where they recommended that life-cycle assessment (LCA) be used to quantify environmental impacts of every major type of 3D printing and compare them to traditional manufacturing methods (Bourell, Leu and Rosen, 2009). Some aspects of 3D printing sustainability include its effect on transportation, manufacturing waste, manufacturing energy, use-phase energy and material recovery for a circular economy. Cases exist, such as General Electric's jet engine nozzle (Freedman, 2011), where 3D printed parts lower the environmental impact of the product in its use-phase. However, because such improvements are difficult to predict and may be limited to aerospace and automotive industries, this chapter focuses on environmental impacts arising from the manufacturing stage.

Impacts from printing plastic components for consumer products and prototypes receive the most attention in the chapter since these appear to be the largest market segments for 3D printing (Beyer, 2014). However, printing parts in metal and other materials will also be discussed, because one of 3D printing's potential benefits is expanding the use of alternative materials. Plastic is ubiquitous today because it can be shaped into nearly any form; 3D printing gives this same ability to many other materials.

3D printing technology applications thus far

3D printing encompasses a wide range of technologies, each a specific combination of print material and printer. For example, thermoplastic materials can only be printed by machines with heat sources to melt and extrude the plastics. Liquid epoxy materials hardened by ultraviolet (UV) light can only be printed by machines with UV light sources. Some systems are more flexible than others.

3D printed models are created using computer-aided design (CAD) software and/or 3D scanners to create digital 3D model files. These CAD files are loaded into printer driver software that runs the printer through whatever procedures are necessary to print the file. Some print driver software is specific to a certain printer or printer family, such as manufacturers Stratasys and Renishaw provide for their printers, while other print driver software is more universal, such as Ultimaker Cura (Ultimaker, 2016) or Microsoft Standard Driver (Microsoft, 2016). Printing processes vary in what they can produce; not all printers can produce all part types.

Many systems print support material in addition to the actual modelling material, in order to prevent parts from collapsing or warping while they are being formed. Many prints require additional support, depending on part geometries and the printing process. This can vary from zero support material to more support material than model material. The support material may or may not be the same as the model material, with various means of removing supports, depending on the process.

Printing processes

Many 3D printing processes exist – far more than can be adequately described in this chapter. Four of the most popular processes are described here: thermoplastic extrusion, inkjet, light-polymerised, and laser sintering, based on their ubiquity in 3D printing and potential for environmental sustainability.

Thermoplastic extrusion melts a solid filament of material through a heated nozzle onto a platform bed or stage to deposit material in the X, Y and Z dimensions. It includes fused deposition modelling (FDM), also called Fused Filament Fabrication (FFF), which is one of the earliest additive technologies and was the first to be open-sourced. FDM is generally lower-resolution than other technologies, but has the particular advantages of being simple, reliable, and low cost.

Common plastics used with this technology are acrylonitrile butadiene styrene (ABS), the same plastic used to produce Lego bricks; polylactic acid (PLA), a plant-derived and biodegradable plastic often used in food packaging; and polyethylene terephthalate (PET), the same plastic used to create most drink bottles and other common packaging. FDM can also be used with modelling clay, plasticine, rubber-like polymers, and eutectic metals.

FDM can be very low waste, when part geometry does not require additional support material. In principle it can extrude any thermoplastic, even with additives. Extrusion printers can only print one part at a time, and print time directly correlates to the amount of material printed.

Inkjet prints like a 2D inkjet printer, but instead of printing liquid ink on paper, it prints liquid binder onto a bed of powder, and then a mechanical wiper spreads another layer of powder over the bed to print the next layer.

It can print many different materials, from plaster to sugar (Molitch-Hou, 2015) to ceramics (fired after printing) to metal powders (sintered after printing). Experimenters at the University of California at Berkeley have used inkjets to print in sawdust, concrete, salt, starch, and more.

This method of printing can offer very high quality – both high resolution and full colour models. In theory, the process can be almost zero waste, because the powder can be reused and no support material is required. Of the few printing methods which have undergone full LCA, inkjet printing of green materials has shown some of the greatest potential for sustainability (Faludi et al., 2015b). However, experimental materials often do not yet meet quality standards for consumer products. Inkjet printers can print more than one part at a time, and print time correlates more strongly to part height than to the amount of material printed.

Figure 5.1. **Experimentally printed part via ink jet**



Source: Faludi, J. et al. (2015b), "Does material choice drive sustainability of 3D printing?", *https://waset.org/Publication/does-material-choice-drive-sustainability-of-3d-printing-/10000327*.

Light-polymerised printing uses liquid photopolymer that hardens when UV light strikes it. This includes stereolithography (SLA) using a UV laser, digital light processing (DLP) using a UV digital projector, and continuous liquid interface production (CLIP) using a UV projector with modified polymer chemistry. SLA, also known as optical fabrication or resin printing, is the oldest type of 3D printing. DLP generally prints faster, and CLIP is an order of magnitude faster.

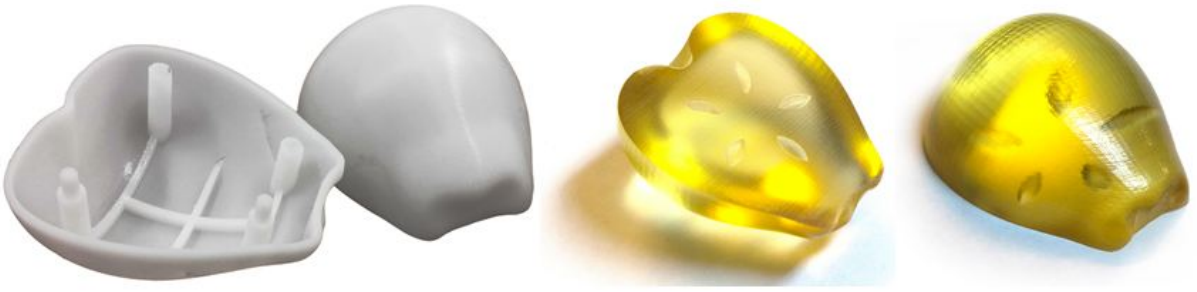
A popular hybrid of photopolymer and inkjet methods is the PolyJet system, using inkjet print heads to print photopolymer onto a surface and then hardening it with a UV lamp. All these methods can make high resolution parts with excellent surface finishes, acceptable for commercial products.

SLA usually requires no support material; others vary by part geometry, and PolyJet requires more support material than other printers listed here. For SLA and DLP, unsolidified liquid polymer can be reused, though not infinitely. Polyjet ink waste is not reusable or recyclable, and current machines are high-waste, averaging 43% even before counting support material (Faludi et al., 2015a).

All 3D printing photopolymers today are somewhat toxic in their liquid form, frequently with a Hazardous Materials Identification System (HMIS) health score of two out of four (3D Systems, 2012), similar to many epoxies. However, they are usually considered non-toxic once solidified.

Photopolymer printers can print more than one part at a time, and print time correlates more strongly to part height than to the amount of material printed.

Figure 5.2. **SLA (left) and PolyJet (right) printed parts**



Source: Faludi, J. et al. (2015a), "Comparing environmental impacts of additive manufacturing vs. traditional machining via life-cycle assessment", *http://dx.doi.org/10.1108/RPJ-07-2013-0067*.

Laser sintering or melting binds a powder together in certain places by heating it with a laser. Most machines such as selective laser sintering (SLS), selective laser melting (SLM), and direct metal laser sintering (DMLS), use a bed filled with powder; the laser strikes the top surface to melt the powder together only in specified locations, then a mechanical wiper spreads another layer of powder over the bed to print the next layer. Other laser melting machines spray the powder from a nozzle while heat-fusing it, such as direct metal deposition (DMD) and construction laser additive directe (CLAD).

Laser melting machines can print in thermoplastics, metals, ceramics, or glass. The most common plastic is nylon and the most common metals are steel, aluminium, and titanium; exotic metal-ceramic alloys are sometimes used for aerospace parts.

Unmelted metal or plastic powder can be reused for later prints, perhaps five to ten times (Slotwinski et al., 2014; Dotchev and Yusoff, 2009), though this is often prevented by quality risk. Support material is not needed to fight gravity, but is often needed to prevent warping. When removed, support plastic is usually landfilled, but support metal is often recycled as machining scraps would be.

Laser sintering printers can print more than one part at a time, and print time correlates more strongly to part height than to the amount of material printed. Laser melting machines can have long warm up and cool down times, as well as significant time required for part removal, so there is an incentive to batch operations.

Figure 5.3. **A laser sintered metal sculpture**



Source: Grossman, B. (2003), "Oldest news", *www.bathsheba.com/artist/news_old_0.html* (accessed 1 May 2015).

Table 5.1 presents a snapshot of the different 3D technologies covered in this chapter in addition to details on how they function on their cost curve.

Table 5.1. **3D printing technologies: Advantages and drawbacks**

Process	Technology	High or low resolution printing	Materials used	Cost curve	Sustainability potential	Batch printing?
Thermoplastic extrusion	FDM, FFF Other extrusion technologies are similar	Low to medium resolution	Commonly ABS, PLA, PET, etc. Other extruders may use more exotic materials	Low to medium cost	Low to high energy use Can be low waste with self-supporting part geometry PET easily recyclable PLA compostable in specialised facilities ABS somewhat toxic and not recycled	No
Inkjet	Liquid binder on powder bed	High resolution. Can print full colour	Commonly plaster or ceramics Alternative materials: sawdust, concrete, salt, starch, sugar, etc.	Medium to high cost	Can be highly energy-efficient when printing in batches Low waste Potentially green materials, but not yet used for consumer products	Yes

Table 5.1. **3D printing technologies: Advantages and drawbacks** *(cont.)*

Process	Technology	High or low resolution printing	Materials used	Cost curve	Sustainability potential	Batch printing?
Photopolymer	SLA,CLIP, DLP, PolyJet	High resolution	Liquid polymer PolyJet can print in multiple materials at once	Low to high cost	Medium energy use; more efficient when printing in batches Liquid polymers somewhat toxic, but can be reused in all but PolyJet Most use little support and generate little waste, but PolyJet is high-waste Solidified polymer not recyclable	Yes
Laser sintering or melting	SLS, SLM, DMLS, DMD, CLAD	High resolution	Thermoplastics, metals, ceramics, glass Common plastic: nylon Common metals: steel, aluminium, titanium	High cost	High energy use; more efficient when printing in batches Most unused powder can be reused Support waste plastic usually landfilled; support waste metal often recycled	Yes

Source: Authors' analysis.

Near-term evolution of 3D printing technology

Several aspects of 3D printing have greatly improved over the past decade. The most important metrics include print quality, print size, print time and material choice. This section details trade-offs in printing technology relevant to the economic impacts and environmental consequences of 3D printing becoming widespread. If 3D technology is scaled up in the coming decades these considerations must be taken into account.

Choosing between print quality and time

3D printing is largely used for prototyping today because high-quality prints remain expensive. However, print quality has improved, and some printer types already print parts acceptable for finished products at a lower cost than other manufacturing methods (e.g. SLA-printed dental crowns) (Bammani, Birajdar and Metan, 2012). Print quality is determined by resolution, tolerance, structural robustness, smoothness of finish, dimensional stability, and other factors. It can also include special abilities, such as the capacity to print multiple colours or multiple materials in the same object. Comparing Figures 5.2 and 5.3 to Figure 5.1 shows how SLA, PolyJet, and SLS generally make higher resolution and smoother surface-finish parts than FDM or the experimental inkjet printing in salt.

Improving resolution often increases production time, thus also cost and energy use. For example, doubling FDM resolution means the print head must traverse twice as many layers, roughly doubling print time. Doubling SLA resolution means using a polymer that needs much longer exposure by the UV laser to harden, thus increasing print time. In both cases, the longer print times mean more energy use because the machine runs at similar power consumption for a much longer time. However, this may not be inevitable. A DLP printer with twice the resolution in the projector might not require noticeably more energy than a lower-resolution projector, because that component of the machine is a small fraction of total power use.

Print cost versus time

The largest barrier to high-quality, low-cost 3D printing at scale is long print time, though this barrier is beginning to diminish. Today, a hollow-shell part just 5 cm x 5 cm x 2.5 cm, such as in Figures 5.1 to 5.3, somewhat similar in mass to that of a mobile telephone case, can take hours to print as opposed to seconds in injection-moulding. While the industry has worked to speed up 3D printing, its main market so far has been prototypers, who appreciate but do not require high speed. The shift in 3D printing towards manufacturing has now made faster print speeds a higher priority for printer manufacturers.

Faster speeds are often simply achieved though larger versions of existing printers, so more parts can be printed at once, but some designs are revolutionary. The CLIP printer by Silicon Valley start-up Carbon3D claims to be 25 to 100 times faster than traditional 3D printers, printing the part described above in minutes rather than hours. This increase in speed can be attributed to the printer's chemistry, which allows a liquid photopolymer to harden continuously as the stage moves, rather than pausing for each layer as all other 3D printer types require (Rolland and Desimone, 2016). Another company, 3D Systems, was developing a printer claiming to be 50 times faster than current speeds in 2014 (McKenna, 2014), though at the time of going to press it had not been released. Such speed increases should greatly reduce the cost per part of 3D printing. Still, it is unclear how much or how fast prices will decrease for customers, because the razor and blade business model is common in the industry. For example, Carbon3D's photopolymer material may be expensive enough to only improve cost per part moderately, despite its large speed increase.

Considering print size

3D printing is expanding print sizes both to very large objects and very small objects. For very large objects, the architecture industry includes KamerMaker's canal house in the Netherlands (Wainwright, 2014) as well as WinSun's concrete panels for a 5-storey apartment building in China (Starr, 2015) and the University of California Los Angeles/Contour Crafting's partnership with NASA to build a moon base (Khoshnevis et al., 2012). For cars, Local Motors has prototyped an electric car with a 3D printed body, the Strati (Davis, 2014). On the small scale, most micro or nano 3D printing has actually been macro-scale printing of materials with micro- or nanoscale properties (Campbell and Ivanova, 2013). However, there has been actual printing at these scales as well. Hybrid microelectromechanical systems (MEMS) techniques have allowed the production of a robotic bee weighing just 90 milligrammes (Sreetharan et al., 2012), quantum-dot light-emitting diodes have been 3D printed (Kong et al., 2014), and lithium-ion batteries have been printed at the millimetre scale, with near-record high energy density (Sun et al., 2013).

In the coming years there will be more progress in the range of sizes 3D printers can produce at low cost. For economic and technical reasons, this evolution will probably come from the large scale rather than the small scale. Small-scale 3D printing is economically disadvantaged because all nanoscale manufacturing must be mass manufacturing if it is to produce useful amounts of a product. Computer chips often contain billions of transistors (Meindl, 2003), and millions of carbon nanotubes only fill a cubic centimetre (Andrews et al., 1999). 3D printers must become much faster to compete economically in this realm (Li et al., 2011). Technology limits play a part as well: lasers used for small-scale 3D printing are

physically incapable of the higher resolution of some other nano-fabrication methods (Li et al., 2011). Hybrids of traditional and 3D printed steps in the electronics manufacturing process can be economic and environmental improvements (Miettinen et al., 2008), but decades will probably pass before 3D printing can fully replace the semiconductor industry for chip fabrication.

Figure 5.4. **Local Motors 3D printed car body**



Photo © Local Motors, Inc.
Sources: Davis, J. (2014), "This is The world's first 3D printed electric car", *www.businessinsider.com/this-is-the-worlds-first-3d-printed-electric-car-2014-12#ixzz3QB6iqz5x* (accessed 15 January 2015); Local Motors, Inc.

Material choice and multiple materials

Expanding material choices allow greater market reach, and the 3D printing industry's material palette is expanding rapidly. The range of materials available for use with 3D printers include: plastics, metals, ceramics, paper and food. Even living human cells can be 3D printed today. They may also come in different states such as powder, resin, paste, or filament. Low-cost desktop FDMs can print flexible or rigid plastics, plastics that change colour with temperature, and plastics infused with wood fibre or carbon nanotubes (Krassenstein, 2014).

Most 3D printer manufacturers use a razor and blade revenue model, selling relatively high-cost proprietary materials. However, open-source communities and hackers frequently make and share new materials. For example, 3D inkjet users have online communities to share recipes for powder and binder mixes (such as vodka and starch, or sawdust).

Perhaps the most important material expansion in 3D printing in coming years will be the capability to print multiple materials in the same part or alter a material's properties from one zone in the object to another. Today, it is impossible to 3D print a mobile telephone – one can only print simple components such as the plastic case, then assemble the electronics into the case. In fact, the only whole products that can be 3D printed are materially simple things like plastic toys or metal jewellery. Everything else is printing components. Printing in multiple materials, however, lets a single part perform the role of

whole assemblies of other parts. Researchers have printed pain-reducing splints, sound-absorbing chaises longues, and other multi-material products (Oxman, 2010), and some commercial printers can already print 14 materials at once (Stratasys, 2015). Still, industry is probably a decade or more from printing a working telephone, both because of material limits and the print size limits discussed above. Multi-material machines printing wiring within plastic parts have been experimentally proven (Silverbrook, 2004), and may soon emerge commercially. If so, it would greatly improve industry's ability to replace assemblies with printed parts.

Printing dissimilar materials together severely reduces their recyclability (Dahmus and Gutowski, 2007), which is problematic for sustainability. However, tuning the properties of a single material within the same part could provide an object that is recyclable, and which replaces an assembly of different materials not recyclable together. Similarly, if different printed materials are all compostable, such as some bioplastics or composites, then there is no need for separation (though injection-moulding could equally well co-mould two different compostable bioplastics). Even wiring could be compostable in the future, as conductive carbon inks can already be made biodegradable (Kilner, 1993). The same is true for incineration, where energy can be recovered from mixed plastics.

Box 5.1. **Print energy**

Trends in printer energy use are hard to predict, as energy prices are too low to drive the market. Desktop FDM machines use much less energy per part than commercial FDM machines (Faludi et al., 2014), but they also have low print quality unsuitable for mass manufacturing. Operating printers more efficiently, such as by SLA/SLS/PolyJet/inkjet machines printing multiple parts at once, or FDM machines printing hollowed parts, certainly reduces energy use per part along with print time per part (Baumers et al., 2013; Baumers et al., 2011b). However, trends driving down print times may or may not drive down energy use. The newly announced Carbon3D printer advertises print times 25 to 100 times faster than others (Rolland and Desimone, 2016), and its power use is probably on par with similar printers (though data has not been released), thus providing a revolutionary improvement in energy use per part. However, other emerging high-speed printer designs such as the system for Google's Ara telephone may achieve their speed gains at the cost of higher power consumption.

Industry expansion

3D printing will expand into many more industries in coming years, but it will be limited by a hyperbolic growth curve: easily entering markets with fewer units produced at high or moderate costs, but unable to penetrate markets with many units produced at very low costs. Thus its growth will affect certain market sectors most; for other sectors it will only affect start-ups and small business groups for some time. Its economics will probably have significant social impacts in both developed and developing countries.

Prioritising costs or volume

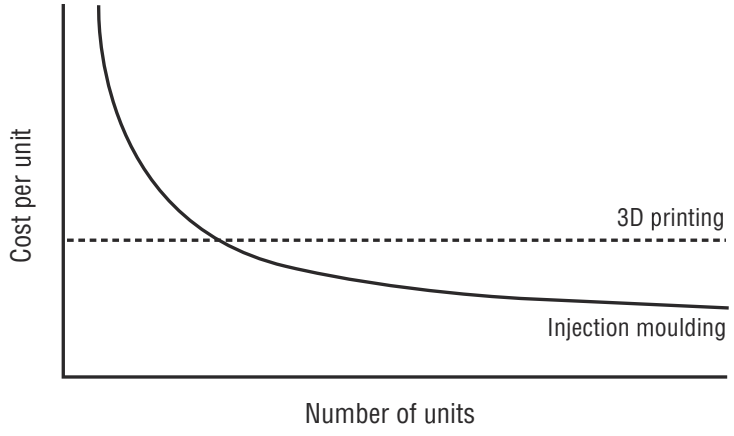
3D printing has a higher cost per unit than traditional manufacturing methods, but no set-up costs between batches of different product lines; this determines the economics of manufacturers switching to 3D printing. Equipment costs vary widely, but both

injection-moulding machines and commercial 3D printers range from tens of thousands to hundreds of thousands of dollars. Assuming that equipment costs amortise away to be roughly equal means that switching from injection-moulding to 3D printing becomes economical when higher costs per part are outweighed by avoiding batch set-up costs. This occurs when:

$$C_{3D} - C_{IM} < \frac{C}{N},$$

where N = number of units per batch, C = cost of tooling/set-up for a new batch, C_{3D} = cost per part of 3D printing N units, and C_{IM} = cost per part of injection-moulding N units (Askin and Goldberg, 2007). Supply chain costs such as transportation and logistics, which are also saved by 3D printing, can be considered part of the set-up cost for this simplistic model. Obviously the lower the 3D printing cost, the larger the market that should switch, but it is a hyperbolic, not linear, curve, as shown in Figure 5.5.

Figure 5.5. **Generalised cost curve of 3D printing versus injection-moulding**



Source: Authors' calculations.

For example, if tooling and set-up for the plastic apple shape in Figures 5.1 and 5.2 cost USD 10 000 and the price per part of injection-moulding is USD 0.50, then 3D printing costing USD 5.50 per part (over ten times the price per part for injection-moulding) is still economical for fewer than 2 000 units. But at 100 000 units, the price of 3D printing must fall to USD 0.60 per part for it to be as economical as injection-moulding. At 1 000 000 units, the price of 3D printing must fall to USD 0.51 per part (within one penny of the injection-moulding cost) for it to be economical.

In industry, these cost crossovers can occur at a range of values. While some studies have found cost crossovers in the tens of parts for metal casting (White and Lynskey, 2013; Atzeni and Salmi, 2012), or hundreds of parts for plastic injection-moulding (Bhasin and Bodla, 2014; Sculpteo, 2014), Conner found that for some parts, plastic SLS can already be less expensive than injection-moulding for runs of fewer than 10 000 parts (Conner et al., 2014). Thus 3D printing will continue to expand rapidly from the prototype market to small-run production, as it is currently doing, but will have much more difficulty expanding from small-run production to mass manufacturing, until 3D printing costs become radically lower.

Bhasin estimated that 3D printing costs would fall by roughly one-third by 2020 (Bhasin and Bodla, 2014), which is not enough to approach cost crossover for millions of units. Bhasin also showed that although 3D printing could radically reduce costs of product transportation, logistics, warehousing, and other holding costs, these are only a small percentage of most products' total cost, meaning that they will not significantly speed up industry takeover. Thus, 3D printing is not likely to replace injection-moulding at the largest scales for at least a decade or two, even after it has become the default production technology for small-run parts. If technical breakthroughs occur this timeline would be shortened, but it will still be limited by simple industry inertia. In the 2D paper printing industry, digital printing became commercially available in the early 1980s, but did not become widespread until the mid-1990s, with many companies taking five years or more from initial use to full integration in production systems (Parnell, 2007).

This conservative assessment should not be taken as an underestimation of 3D printing's growth curve; many industries produce parts in the thousands or fewer. High-technology industries such as aerospace, defence and certain medical devices often produce parts in the mere hundreds. Some of these parts are already being made by 3D printers more economically than with other methods, as mentioned in the introduction. Mass-customised products such as individually fitted hearing aids and tooth fillings are already cheaper to 3D print because each unit is different even though they are produced in the millions. The potential exists for medical prosthetics and elite sporting equipment to be the next frontier in low-volume printing.

Other industries that have not yet been penetrated by 3D printing, but where this is likely in the next several years include those manufacturing toys, precision machinery, optics and miscellaneous luxury goods. Objects produced in a five- to ten-year timeframe may encompass designer housewares, furniture and clothing. These industries all have what McKinsey calls a relatively high "value density" and "labour density" (McKinsey Global Institute, 2012), meaning they are relatively high value per mass of material, and a relatively high percentage of the cost of manufacturing is from labour, which 3D printing reduces or eliminates. Toys may be an especially likely sector, because they are a highly volatile seasonal market with unpredictable demand for "must-have" items.

3D printing can also increase production instantly to arbitrarily high levels, without the need to manufacture and store goods in warehouses beforehand. Another advantage is the elimination of tooling costs on several production lines on short notice. The production of furniture and clothing are more difficult to predict because most 3D printer research and development is not focused on those markets. One example from the textile industry is Nike's Flyknit shoe line which uses 3D computer-controlled knitting, and been a great commercial success (Townsend, 2012).

Prioritising costs or size

Product size will continue to be a limitation. Smaller parts are more cost-effective to 3D print because print time and material consumption are the dominant costs for 3D printing. Both relate to the size of parts printed; smaller parts are more economical to 3D print. In this vein, the jewellery industry is becoming another early adopter of 3D printing, since it is often an industry producing few units at a high cost per unit. In contrast, the automotive industry is unlikely to have 3D printing as a significant percentage of production for a decade or more, because it requires many large parts in addition to high-

volume production at medium to low margins. However, this assumption is inconclusive. Automotive tooling already constitutes approximately 18% of the 3D printing industry and innovations like the Strati vehicle may shift the industry towards finished parts.

The architecture industry poses the largest size challenge, but may also be a golden opportunity for 3D printing, as the industry is primarily bespoke and highly labour-intensive. As mentioned above, 3D printing has entered the industry. However, as promising as these initial efforts are, the building industry is notoriously conservative. Even if today's 3D printers were unequivocally higher quality and lower cost than manual construction, it would probably still take a decade for the innovation to penetrate the market without policy incentives. Any such incentives would probably encounter political resistance, due to the number of jobs that would be lost as a result of automated construction. At the other size extreme, integrated circuit electronic parts are too small for 3D printing to penetrate soon. They have much higher-value density than toys or clothing, but sophisticated circuitry will remain beyond the range of 3D printing for the foreseeable future.

Box 5.2. **Social impacts in developed and developing countries**

Significant social impacts will accompany the environmental consequences of 3D printing. One evolution will be the shifting business landscape. Access to 3D printers can empower start-ups and small manufacturers. Developed countries may see a "reshoring" of production. Developing countries may see an uptick in entrepreneurialism. However, it will exacerbate the loss of jobs in manufacturing.

Start-up companies in any industry begin by producing parts in the thousands or fewer. 3D printing's economical production of small-run parts will enable more companies to start manufacturing with less capital. It will also allow companies of any size to spend more time in product development, making small runs of products and getting feedback from clients in order to improve them before producing in higher quantities. As global trends show increasing "fragmentation of demand" where more versions of products have shorter product cycles, this becomes an increasing share of markets (McKinsey Global Institute, 2012). However, this can have the negative side effect of enabling more planned obsolescence.

One socio-political disadvantage of 3D printing lies in the elimination of skilled manufacturing labour through automation. A sample prototype for Berkeley research (Faludi et al., 2014) took several hours of skilled machinist labour to create with the help of a highly automated computer-numeric-control (CNC) mill, but only took a few clicks of a mouse to 3D print. This trend will probably mirror the transformation of the 2D paper printing industry in the 1990s. That industry lost many jobs, but new jobs emerged. "Computerised typesetting programs inevitably brought deskilling, but original skills, learned and used by workers over many years of rapidly changing technology, did remain relevant, and the acquisition of new skills associated with computerisation was regarded favourably" (Parnell, 2007). It is unclear how many jobs will disappear or merely change for manufacturing transitioning to 3D printing.

A benefit of 3D printing's reduction of labour costs is potential "reshoring", the practice of returning manufacturing from low-wage countries to high-wage countries (Tavassoli, 2013). The extent of this reshoring is difficult to predict, but it will probably follow the growth curve of industry penetration listed above: first high-margin, low-volume industries, then lower-cost, higher-volume industries. Recall, however, that 3D printing generally only produces

Box 5.2. **Social impacts in developed and developing countries** *(cont.)*

parts, not whole products, and will continue to do so until multi-material printing becomes far more sophisticated (which will take many years). Products will still require assembly somewhere, and this may limit the extent of reshoring. Still, potential exists for large gains, as 3D printing can fabricate complex parts that would previously have been assemblies, thus enabling less assembly labour.

Some have touted 3D printing as a boon for developing countries (Birtchnell and Hoyle, 2014), because of the potential to eliminate supply chains, thereby solving distribution issues in countries with little infrastructure. This optimistic outlook ignores the economic damage that reshoring production to developed nations would have on developing economies, but proponents have generally focused on extremely rural areas, where the "poorest of the poor" live, which would not be producing offshored goods. Proponents forget that printers today are limited mostly to producing parts, not whole products, and more importantly that the printers themselves need supply chains for maintenance and repair of both themselves and the computers required to 3D model the objects being printed. If a village does not have a supply chain for a simple plastic part, it certainly does not have a supply chain for a computer motherboard. Since the 1970s and 1980s the developing world has seen many well-intended solar electrification projects fail due to a small component breaking with no means to repair it (Dichter, 2003). As Birtchnell admits, 3D printing for development is optimistically a decade off because it requires affordability, "flexibility" (reparability and upgradability), simplicity, scalability, and quality to enter the "Goldilocks zone" of usefulness (Birtchnell and Hoyle, 2014). Design for development usually refers to its demographic as "the base of the pyramid" because it is a very large number of people with very little money. The cost curve described earlier shows that this is the opposite of 3D printing's advantages.

Still, 3D printing for development could prove quite beneficial in different scenarios in the major cities of poor countries. Developing countries have leapfrogged past wired telephones to cell phones with enormous economic and social benefits to millions of people; a similar leapfrogging could happen with small urban manufacturers. The greatest benefit for developing countries is probably the same as in developed countries: allowing start-ups or small businesses with little capital to begin manufacturing on a small scale, then using the earnings to finance expansion into mass manufacturing. Instead of 3D printing taking the place of centralised manufacturing and distribution networks, 3D printing could take the place of venture capitalists. Then, once entrepreneurs are producing at scale with traditional manufacturing methods, they can produce products for large numbers of people with little money, helping economic development at scale. 3D printing will have the added benefit of helping developing world start-ups to circumvent supply chain infrastructure limitations until they have grown enough to afford their own infrastructure. But because the 3D printer itself needs infrastructure and a supply chain, it seems more useful as a stepping stone than a destination. Future studies should investigate these scenarios compared to rural manufacturing.

Likely environmental impacts of widespread 3D printing

Widespread 3D printing will not uniformly increase or decrease the environmental impacts of manufacturing. Changes will depend on the specific item produced. Most products require multiple parts made through a mix of manufacturing methods, e.g. moulding, casting, stamping and bending, extruding and welding. The impacts of these

technologies are varied and highly dependent on the parts being produced. Therefore, to accurately forecast the environmental implications of replacing these with 3D printing, studies should compare 3D printing to each sequence of technologies it replaces, for each relevant product type and material. The 2009 RAM recommended such research (Bourell, Leu and Rosen, 2009), though few such studies have been published to date. This chapter discusses only two benchmarks: 3D printing compared to machining and injection-moulding.

Broad generalisations about the advantages of 3D printing in comparison to machining or injection-moulding cannot be accurately made. Environmental impacts vary widely depending on printer type, part geometry, machine utilisation rate (idle time and efficiency of bed packing for many printer types), print set-up and material. Given these caveats, for a "typical" hollow-shell plastic or metal part, 3D printing is generally lower-impact per part than machining, but higher impact per part than injection-moulding at scale. The largest environmental impacts generally come from printing energy and material use, although this varies by printer, material choice, and usage scenario. In addition, the technology is changing rapidly, meaning that some experimental systems today may be substantially lower-impact than other manufacturing methods, but more research is required to support these claims.

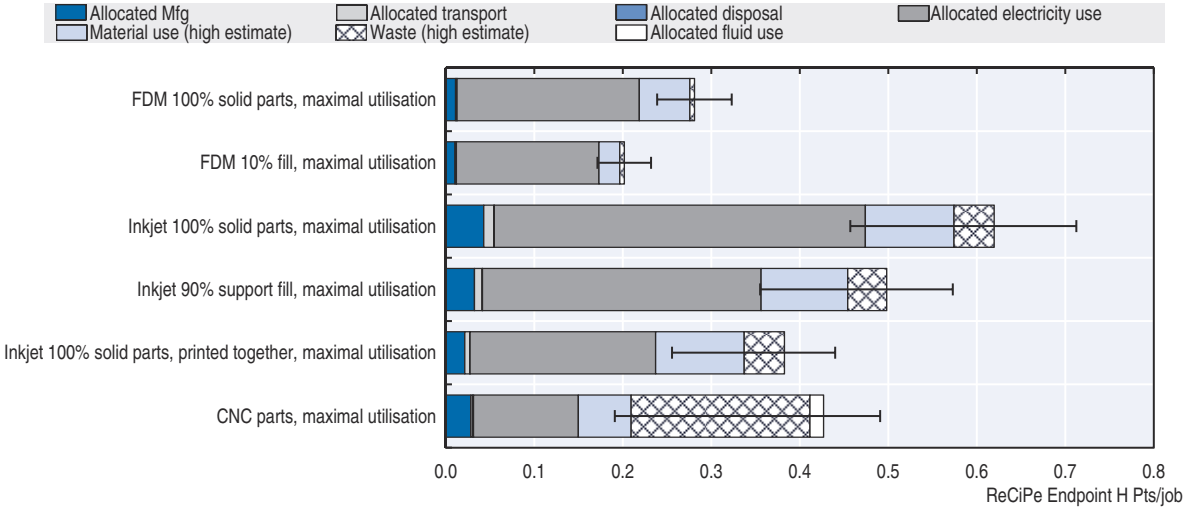
3D printing compared to traditional machining

The next five to ten years will probably see 3D printing supplant much (perhaps even most) machining of parts, but this is unlikely to create large shifts in the environmental impact of the manufacturing sector on a global scale, because machining's market niche is small. Machining is the main method for prototyping and producing limited amounts of complex-geometry custom parts. 3D printing is already significantly altering these markets for both plastics and metals. For plastics, prototypes and small-run production parts are 3D printed by FDM, SLA, and SLS; for metals, they are printed by e.g. DMLS, SLM, DMD or CLAD. Boeing alone has already replaced machining with 3D printing for over 20 000 units of 300 kinds of parts (Davidson, 2012). However, machining is a small niche – statistics from the US Bureau of Economic Analysis show machining categories to comprise less than 1% of total manufacturing dollars (BEA, 2014).[1] Thus, even dramatic environmental improvements from replacing machining with 3D printing will not noticeably reduce manufacturing sector impacts on a global scale.

3D printing generally produces parts with lower environmental impacts per part than machining, but there are many exceptions – some part geometries are more efficient to machine than to print, different printers have very different impacts per part, and even a given printer can have very different impacts per part depending on several factors. For plastic parts, two studies (Faludi et al., 2015a; Faludi et al., 2014) showed that changing printer utilisation causes more variation than the difference between 3D printing versus machining. Machines which predominantly sit idle have far higher environmental impacts per part than machines producing parts 24 hours per day, seven days per week, whether they are 3D printers or milling machines. Thus, maximising utilisation is a top priority for sustainability in 3D printing. These studies also showed that some 3D printers have higher impacts per part than others due to higher energy use, waste, and material toxicity. Finally, comparing the two studies shows that producing hollow-shell part geometry rather than solid-block geometry reduces environmental impacts per part for 3D printing, but increases them for machining. Thus, some solid-block geometries can be machined for less impact than they can be if 3D printed, even if 3D printing is lower-impact for other parts.

For example, Figures 5.6 and 5.7, derived from the aforementioned studies, show LCA comparisons of machining via a CNC mill versus several 3D printers, all producing parts 24 hours per day, seven days per week. The LCAs use the ReCiPe Endpoint H method (Goedkoop et al., 2009), which creates a single overall environmental impact score from 17 different types of impact, including climate change, acidification, eutrophication, atmospheric particulates, fossil-fuel depletion, mineral depletion, human toxicity, and others. These impacts can be grouped by the stage of the life cycle under which they occur: impacts relating to manufacturing, transport and disposal of the printer or CNC mill, impacts associated with electricity use during part creation and/or idling, impacts from materials use in the final parts produced, impacts arising from waste materials (be it model material or support material), and finally, impacts of the mill's fluid use.

Figure 5.6. **Environmental impacts of one CNC mill versus two 3D printers, all running at maximal temporal utilisation, making solid parts**



Note: The black horizontal line at the end of each bar represents the error range.
Source: Faludi, J. et al. (2015a), "Comparing environmental impacts of additive manufacturing vs. traditional machining via life-cycle assessment", *http://dx.doi.org/10.1108/RPJ-07-2013-0067*.

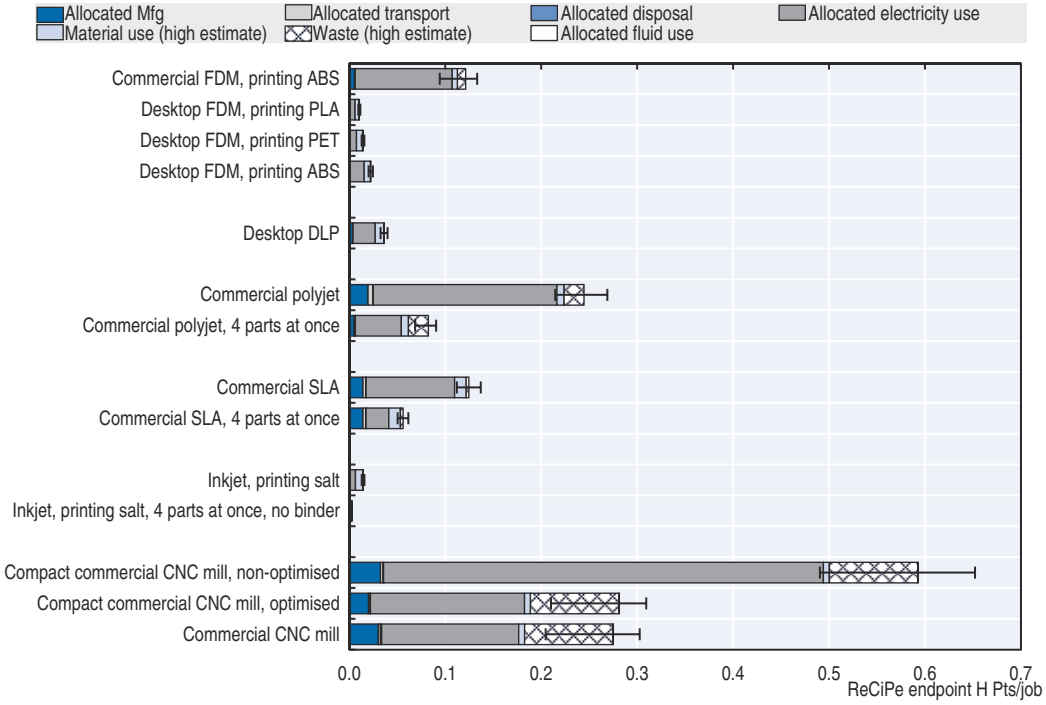
StatLink http://dx.doi.org/10.1787/888933473851

Figure 5.6 shows one CNC mill making solid-block plastic parts, compared to two different scenarios of a commercial FDM printer and three different scenarios of a PolyJet printer making the same solid-block parts. The CNC mill performs better than two scenarios of the PolyJet, and is within error bars of the commercial FDM. However, Figure 5.7 shows two CNC mills making hollow-shell parts, compared to eight 3D printers in 11 scenarios making the same hollow-shell parts. There, the CNC mills always have higher environmental impacts than all the 3D printers (though sometimes within error bars). Figure 5.7 more fairly represents most plastic consumer product parts, such as a telephone case, but a few product categories are solid plastic.

Figures 5.6 and 5.7 also show the wide variation among printers and scenarios. Some printers have far lower impacts per part than others, and the impacts change based on part type and machine utilisation. Policy makers should keep in mind that this is not a monolithic field. For example, the inkjet printing in salt has the lowest impact of all machines shown, reducing impact by over 90% compared to machining, but PolyJet

printing sometimes scores worse than machining. Unfortunately, today some of the lowest impact machines, such as the desktop FDM, have the poorest print quality. Conversely, some of the highest-impact machines, such as PolyJet, have some of the best print quality.

Figure 5.7. **Environmental impacts of two CNC mills versus eight 3D printers, all running at maximal temporal utilisation, making hollow parts**



Note: The black horizontal line at the end of each bar represents the error range.
Source: Faludi, J. et al. (2015a), "Comparing environmental impacts of additive manufacturing vs. traditional machining via life-cycle assessment", *http://dx.doi.org/10.1108/RPJ-07-2013-0067*; Faludi, J et al. (2015b), "Does material choice drive sustainability of 3D printing?", *https://waset.org/Publication/does-material-choice-drive-sustainability-of-3d-printing-/10000327*.

StatLink http://dx.doi.org/10.1787/888933473864

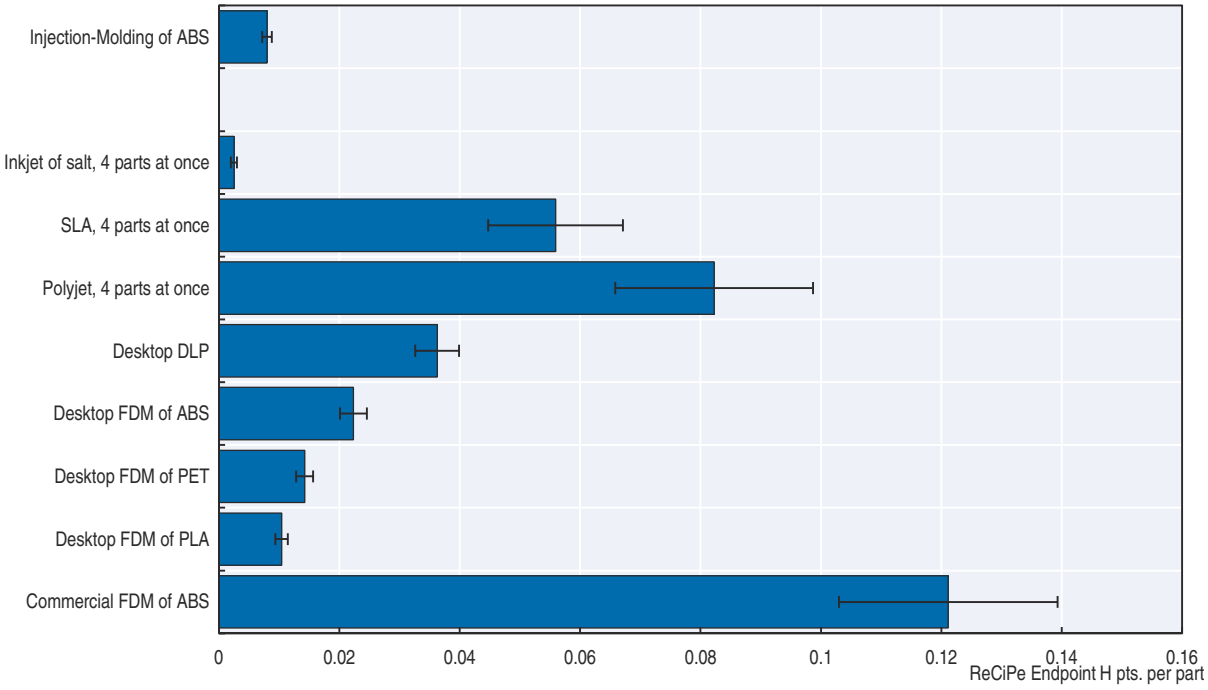
In both graphs above, the environmental impacts of 3D printing are largely dominated by energy use during printing. For CNC mills, however, material waste is a significant, sometimes dominant, impact. Thus, switching from machining to printing will reduce material waste impacts, but may not reduce energy impacts. It is possible to increase energy impacts beyond the savings in waste impacts. The embodied impacts of producing the machines are insignificant for any printer or CNC mill when producing parts 24 hours per day, seven days per week, though this is no longer true at low utilisation (not shown in these graphs, but in the cited studies) (Faludi et al., 2014; Faludi et al., 2015b).

Other studies have confirmed a wide variation in energy use per part across different printer types and scenarios, including metal printers such as SLS, DMLS, SLM, CLAD; they also confirm that while 3D printing is often lower energy use per part than machining, some circumstances can cause it to be higher (Yoon et al., 2014; Serres et al., 2011; Morrow et al., 2007). High utilisation can also be extremely important for metal printers. Baumers showed that energy use during laser sintering is "job-dependent, time-dependent, geometry-dependent, and Z-height-dependent" (Baumers et al., 2011a) and that high utilisation reduced energy use per part from as little as a few per cent to as much as 98%, depending on the printer type (Baumers et al., 2011b).

3D Printing versus injection-moulding

Injection-moulding is the most common manufacturing method for plastic consumer product parts. The potential for major changes in environmental impact due to replacement by 3D printing could be significant if they happen on a large scale. For example, Figure 5.8 compares the environmental impact of injection-moulding (based on standard LCA data) to that of different 3D printing technologies (based on empirically measured data from Figures 5.6 and 5.7). Rather than dividing each bar into components of e.g. energy or waste, the graph displays one bar per printer and material type.

Figure 5.8. **Environmental impacts per part of injection-moulding versus several kinds of 3D printing at maximal utilisation**



Note: The black horizontal line at the end of each bar represents the error range.
Source: Authors' calculations.

StatLink http://dx.doi.org/10.1787/888933473878

In Figure 5.8 injection-moulding has lower environmental impacts per part than any 3D printing technology in widespread use today, for large print runs. Injection-moulding's fixed impacts, such as creating tooling and set-up time, are amortised across hundreds of thousands or millions of parts produced. Desktop FDM of PLA plastic causes 20% higher impacts than injection-moulding of ABS (although this is nearly within uncertainty margins), while one commercial FDM of ABS causes roughly ten times higher impacts. This does not apply to small production runs, such as hundreds of parts (Telenko and Seepersad, 2012); both economics and environmental impacts can favour 3D printing for small-scale production. These results do not include increased exposure to toxic particulates of personnel in offices or homes with 3D printers rather than industrial environments with safety measures (Stephens et al., 2013). Some researchers have shown that 3D printers powered by solar panels or printing in PLA can have lower impacts than injection-moulding

ABS (Kreiger and Pearce, 2013), but these arguments may not capture the full picture, because injection-moulding machines can be solar-powered or use PLA plastic with equivalent ease to 3D printers. If they were operated in such a way their impacts would be similarly lower.

The only technology in the graph above that scores better than injection-moulding is 3D inkjet printing in salt. This is a low-energy process using chemistry instead of melting to bind material together. This is an experimental material that currently does not match the resolution or surface finish of injection-moulded parts. However, its score shows an almost 70% reduction in impact per part. A compromise between this method and more conventional technologies could be an environmental improvement over injection-moulding.

The inkjet printing method is well-established and commercially successful, warranting further research and development to improve print quality without compromising environmental impacts. This technology presents low operating costs, because rather than buying an expensive proprietary powder and liquid from the printer manufacturer, the powder and liquid are an open-source recipe of common inexpensive materials such as fine-ground salt, maltodextrin, isopropyl alcohol, and water. While at an individual level expertise is required to prepare the ingredients, at scale such materials would be inexpensive and comparable to the cost of plastic granulate for injection-moulding.

Impacts on greenhouse gas emissions

Widespread replacement of injection-moulding with 3D printing could notably increase or decrease greenhouse gas emissions on a global scale. These changes would probably be gradual. In terms of global resource depletion, 3D printing is unlikely to make significant changes even in the long term.

For greenhouse gas emissions, all industry worldwide accounts for roughly 29% of emissions, with other major sources being buildings, transportation, and agriculture (Ecofys, 2013). Statistics on what percentage derives from injection-moulded plastics are difficult to find, but comparing LCA data from two sources (Hendrickson et al., 1998; Bjorn and MacLean, 2003) suggests plastic injection-moulded products may account for 0.5% to 2% of global greenhouse gas emissions. Shrinking all of these emissions by 70% would be a noticeable improvement, and increasing them ten-fold would pose a severe problem. However, even with these large differences in technology impacts, the global-scale consequences of shifting from injection-moulding to 3D printing will probably occur slowly. As previously described, 3D printing's cost curve implies that printing will only replace injection-moulding for small-run production in the next several years, taking over moderate production volumes as costs fall and quality improves, with great difficulty (and therefore many years) replacing high-volume low-cost production.

As regards resource depletion, worldwide plastic use for injection-moulding totals approximately 39 million tonnes per year (Thiriez and Gutowski, 2006). The percentage of total world material extraction this represents is uncertain, but for the United States, less than 5% by mass of total material extraction is petroleum products (Matos, 2012), and of that less than 3% is used to make plastics (US EIA, 2014); therefore, all plastic use (including injection-moulded plastic) comprises perhaps 0.1% of total material consumption by mass. As the difference between 3D printing material use and injection-moulding material use are within a factor of ten of each other, switching to printing is unlikely to make significant differences on the global scale.

Potential for environmental sustainability

Widespread 3D printing can potentially help the environment in many ways, though probably not in the ways most propounded today. Two popular fallacies are that 3D printing could virtually eliminate the negative externalities associated with transportation and waste; and 3D printing is also likely to reduce plastic recycling rates. Green 3D printing realities lie more in aligning economic incentives with environmental impacts, enabling lean production, expanding material alternatives, and increasing energy efficiency in the use-phase of some products. It can be a step closer to industry building as nature does by using compostable biopolymers to solve waste concerns. It also has the potential to benefit society by providing more people with access to the means of production.

Green 3D printing misconceptions

One popular fallacy is that 3D printing will drastically reduce externalities related to transportation of goods, because manufacturing will shift away from centralised factories to regional factories or even consumers' own homes. This is not quite true, and even if it were true, this effect would not have a large aggregate environmental impact. It is not quite true because 3D printers today can only print parts, not whole products, unless those products are extremely simple. Most products must still be assembled in factories, out of a combination of printable and non-printable parts, and shipped to customers. Even for printing 100% on site, feedstock materials for 3D printers still need to be transported, even for multi-material printers that can print whole products rather than just components. 3D printing could indeed reduce transport for businesses selling many different products all made from one material. For example, an automotive repair shop might stock 500 different components made from the same steel alloy, and could radically reduce their transportation impacts by only shipping and warehousing that steel alloy powder to print different parts on demand. Furniture shops might indeed reduce their costs linked to shipping bulky items that are mostly air, instead shipping compact spools of wood-plastic composite.

Even when transport reductions are large, their impacts are usually small compared to manufacturing impacts. Multiple studies (Hanssen, 1998; Hunter, 2013; Apple, 2014) have shown that for most consumer products (be they electronics, furniture, car parts, housewares, clothing, etc.), transportation generates a small percentage of the product's total cradle-to-grave environmental impacts, with occasional exceptions. Even if 3D printing did entirely eliminate transportation related externalities via molecular-scale local material sourcing (Stephenson, 2003), it would barely matter for most products. Aside from a few exceptions, the environmental impacts of manufacturing and energy use during product life are far more important, making these areas a priority for policy makers.

Another persistent fallacy is that 3D printing will automatically be more sustainable because it "eliminates waste" whether of final products or input materials. Some types of 3D printers can indeed produce parts with almost no waste. For example, when FDM machines print parts with no support material, waste can be a fraction of a per cent of part mass. SLA and inkjet machines can also be run with negligible waste. However, long part geometries with steep overhangs can require more support material than actual model material (i.e. greater than 50% waste). Most 3D prints fall in between these extremes, requiring a small to moderate amount of support material.

However, support material is not the only source of waste; other sources vary by printer type. A PolyJet printer wastes 43% of all its liquid polymer in both model and support

material, so a print requiring as much support material as model material would actually cause 65% waste (nearly twice as much waste as the final part). Moreover, liquid PolyJet model material is more toxic per kilogramme than standard injection-moulding plastics like PET or ABS. For plastic sintering, Telenko and Seepersad calculated that "up to 44 per cent of the material that enters the SLS process might be wasted" (Telenko and Seepersad, 2012). For metal sintering, Kellens reported unused powder losses of 20% of part mass (Kellens et al., 2011), with the rest reused. Even some FDM printers generate excessive waste through poor design choices. For example, the 3D Systems Cube desktop FDM printer uses proprietary cartridges of printing filament. The cartridges are produced from two types of plastic over-moulded, which renders the cartridge unrecyclable (Grenchus et al., 1998). Since the mass of plastic comprising the cartridge is greater than the mass of printing filament within, this causes over 50% waste even if the printer is operated at perfect efficiency. Such situations are rare, and some manufacturing methods produce more waste. Machining a hollow part from a block of plastic typically creates large amounts of waste, often over 80%, therefore 3D printing can be generally assumed to cause less waste compared to such methods. However, mass-manufactured plastics are typically moulded, not machined.

Injection-moulding is an efficient process: waste or scrap rates are reported ranging from 10% (Thiriez and Gutowski, 2006) to 5% (Olmsted and Davis, 2001) to 1% (Frischknecht et al., 2005). Thus, while some 3D printing wastes less than injection-moulding, some wastes significantly more. Even if waste were always reduced, it would not always be important. As shown in Figures 5.6 and 5.7, energy use is by far the largest environmental impact of 3D printing. Increasing energy use per part produced can overwhelm material savings to increase total environmental impacts. When printers do reduce total environmental impacts, they do so by combining low waste with low-impact material choice and low-energy processing.

Aligning economic incentives

The clearest way in which 3D printing is likely to improve manufacturing sustainability is by aligning economic incentives with environmental impacts. In traditional production, both prototyping and mass manufacturing, complexity of design is more expensive than materials or energy. This has led to material and energy inefficiency when producing parts. In 3D printing, by contrast, materials are expensive, but design complexity is free. In the coming years this should lead to parts made complex to save material. Software already exists to optimise part geometry for minimum material mass while fulfilling specified physical requirements such as stresses of given directions and magnitudes (Within, 2011). Energy is less expensive, but for printer operators, energy use is proportional to print time, effectively causing energy to be expensive and incentivising printer operators to save energy through the complexity of print setups. However, there is no such incentive for printer manufacturers to design energy-efficient printers. At the time of going to print, there was not a strong correlation between power use and print time within a given printer type (Yoon et al., 2014). Thus, the incentive to save energy is weaker than the incentive to save material mass.

Enabling lean production

Lean production can benefit from 3D printing. Another aspect of economic incentives aligning with environmental impacts is that the cost to print the millionth part is the same as the cost to print the first part. This is unlike injection-moulding and other mass-manufacturing methods, where the millionth part is far less expensive than the first part,

even though it consumes similar amounts of material and energy. Since 2D digital printing has allowed such on-demand production for two decades, product packaging can be made to order along with 3D printed products, avoiding waste there as well. This is the true way in which 3D printing can "eliminate waste" – by eliminating overproduction. Warehousing extra inventory incurs financial costs, but for mass manufacturing these costs are usually much less than machine set-up and tooling costs, so parts are mass-manufactured in advance and held in warehouses for predicted levels of demand that may or may not ever come. By contrast, for 3D printing, there are virtually no set-up or tooling costs, and thus warehousing costs become significant. This enables leaner manufacturing and reduces the economic incentive to overproduce. The extent of this benefit varies by market sector, but unsold goods may average 4-5% of most sector revenues (Bot and Neumann, 2003). This does not even include reduction of work-in-progress parts within a factory, which can be significant.

However, expectations of avoiding overproduction from eliminating economies of scale should be tempered by expectations of adding overproduction from the ease of printing, as described earlier. This will include both excess parts printed and many failed prints, which is a form of waste. Because 3D printing is such a rapidly expanding field, operators often push the limits of printers or operator expertise, which results in a higher failure rate than status-quo manufacturing methods. Today, failure rates can be high for some applications (Baumers, Holweg and Rowley, 2016). However, in the long run this is not likely to be a significant problem, because industry is already working diligently to reduce failed prints for customer satisfaction purposes. Coming years will see improvements with no policy intervention needed.

Encouraging the use of green materials

3D printing will probably expand the number of sustainable materials available to manufacturers, and/or the range of physical properties possible with sustainable materials. Some of this will be due to 3D printing's technology, some due to its economics. One frontier will be the availability of "tunable" materials, capable of changing physical properties according to printing parameters.

Today's ubiquity of plastic is largely due to the fact that it can be shaped into nearly any form; 3D printing could give this same advantage to many other materials. Printed materials today include not only plastics and metals, but ceramics, food, bonded powders of salt, sawdust, or starch, even living human tissue. Even within more traditional plastic printers, specific processing details can encourage different materials. For example, the thermo-physical properties of PLA bioplastic are more favourable than ABS plastic for FDM printing, thus FDM has coincidentally encouraged PLA use. Alternative metals and ceramics can also be enabled by 3D printing. The jet engine nozzle cited in the introduction was 3D printed in a cobalt chromium ceramic alloy, an exotic material which was not previously feasible for such a part because it was not suited to prior manufacturing methods (Beyer, 2014). When searching for new materials, the greatest environmental promise will come from the production of objects from abundant, renewable, non-toxic ingredients using low-energy processing methods.

Today, unfortunately most 3D printing materials are not environmental improvements over the status quo, and some are worse. For example, powdered metals require more energy to produce than the ingots used by other manufacturing methods (Granta Design, 2009). As mentioned earlier, the UV-cured resins used for SLA, DLP, and PolyJet are somewhat toxic in

their liquid form (3D Systems, 2012), but usually considered non-toxic once solidified. ABS plastic has been rated as fairly hazardous to produce and is rarely recycled municipally (Rossi and Blake, 2014), and 3D printing in a home or office can expose bystanders to inhaled particulates (Stephens et al., 2013), but it is common in injection-moulding as well. One existing success story is PLA bioplastic: considered expensive and problematic by mass manufacturers, it has become one of the most common materials for hobbyist FDM printing because its physical properties are amenable to the process, as described below.

Economic differences may enable green materials in 3D printing as much as technological differences. Alternative materials such as PLA are frequently more expensive per unit than status-quo materials, due to smaller-scale production, but labour costs often far outweigh material costs. 3D printers can greatly reduce labour costs, thus enabling some companies to use higher-cost materials while still lowering overall manufacturing costs.

Another economic incentive for green materials in 3D printing is the removal of economies of scale. Complexity is expensive in traditional manufacturing, but material mass is not, thus encouraging a small palette of consistent materials used en masse. 3D printing lowers the cost of switching from one material to another, because no tooling is required. One part can be printed in thermoplastic on one printer while the next part is printed in sawdust on another printer, or perhaps even the same printer configured differently. Many 3D printing companies even unintentionally incentivise users to experiment with alternative materials, by using the "razor and blade" business model. They sell printers at relatively low margins to make most of their profits from high-margin proprietary materials used for printing. This, along with the industry's connections with the hacker culture and "maker" culture, encourages people to experiment with their own materials.

Green materials in 3D printing are limited by technical availability, commercial availability, substitutability, print quality, and acceptance in industry. Technical availability includes the compatibility of new materials with the various 3D printing methods. For example, wood cannot be used for SLA processes because it does not bond on exposure to UV light. Commercial availability includes the production scale and cost of these materials: sawdust and salt have been proven to work technically, but lack commercial distributors. Substitutability consists in matching a material's properties to its use. For example, even though PLA can be printed by the same printer that prints ABS, many professionals disdain PLA because ABS has a higher melting point and other characteristics they desire. Thus PLA has largely been limited to hobbyist markets. Print quality includes many factors, such as the colour of recycled plastics being contaminated from mixing two different colours, or inkjet printing of salt not providing as smooth a surface finish as PolyJet printing. Even if all of these challenges can be overcome, acceptance in industry can lag by years due to sunk costs, economies of scale, or conservatism. While experiments in greener materials and methods are tiny fractions of the market now, they could be encouraged by policy or development funding. The industry's current explosive growth rate provides an opportunity to dethrone entrenched materials and printing methods.

Tunable materials may open wide possibilities for sustainable materials by allowing a small number of ingredients to fulfil the roles of many. This can help avoid the need for mining exotic materials, simplify toxicity screening, and perhaps improve recycling or composting. Tunability can include both true tuning of material properties, or uniform material properties in a structure that is geometrically tuned to provide different properties in different regions. For a geometry example, today many products use a "living hinge," an

area where a part is thinner than elsewhere, allowing the part to bend at that location even though the material is the same there as in thicker locations (Mraz, 2004). For a material example, the castable cellulose pulp material Zelfo allows "values for density from 0.5 g/cm^3 (gramme per square centimetre) to 1.5 g/cm^3, for tensile modulus from 1 500 MPa (megapascal) to 6 550 MPa, and for tensile strength from 7 to 55 MPa" (Svoboda et al., 2000). It is also recyclable and biodegradable.

An example of using sustainable and tunable materials in 3D printing is the Massachusetts Institute of Technology (MIT) method, water-based digital fabrication (WBDF), originally called "water-based robotic fabrication". It polymerises compostable polysaccharides such as starch or cellulose with water in a robot arm extruder (Mogas-Soldevila, Duro-Royo and Oxman, 2014); these are renewable raw materials. Its extrusion process is chemistry-based, so its printing process can use much less energy than melting plastic. Its chemistry is water-based, so it involves far fewer toxins than standard plastics (all three of the main ingredients of ABS are toxic, even though ABS itself is generally considered harmless to the end user; similarly, the UV-activated photopolymers used by SLA, PolyJet, and DLP are considered toxic until solidified). WBDF is not only compostable, but dissolves in water within minutes (however, this property would probably be changed to normal compostability for commercial goods, as it would be inconvenient for many applications). Finally, its material properties can be "tuned", adjusting strength and rigidity in different areas according to the printing process. This tuning allows one material to replace multiple different materials. Funding for research and development is needed to improve print quality and material properties for such methods, so they can become viable commercially. If successful in 3D printing, such technologies might also expand into injection-moulding and other plastics manufacturing.

Composting and recycling possibilities

Some experimenters hope 3D printing will encourage recycling, but market forces are largely driving the opposite; compostability is another treatment option, for non-metallic parts, but this also has some drawbacks. Several printing technologies require non-recyclable polymers, and as the future brings more multi-material printers, these printers will make even recyclable plastics unrecyclable by making them inseparable from each other. However, recycling may be enabled by 3D printers reducing part count in products, reducing material variety or using expensive materials. Some 3D printing can and does use recycled material. Composting 3D printed products could in theory increase in the future, but there are also a number of risks and it is not clear whether this treatment option would be superior to incineration in state of the art facilities.

Recycling for 3D printing suffers from the same problem all recycling does: sorting. Proponents argue that 3D printing can increase recycling rates because recycling to local 3D printing, rather than centralised municipal-scale systems, avoids transportation costs. However, this will be insufficient motivation because transportation costs are low (Bhasin and Bodla, 2014). The primary barriers to recycling are not transportation but sorting and quality control to ensure usable material. Plastics come in thousands of different polymers, grades, colours, and mixes of additives for flexibility, strength, UV-resistance, or other properties. Metal types and grades also vary widely. Recyclers today rely on hundreds of thousands or even millions of dollars' worth of sorting infrastructure, including multi-stage sorting tools using water baths, magnets, electrostatic charge, and other systems, spectrometers to identify plastics and metals, conveyors and storage of materials, etc. Such

infrastructure has inherent economies of scale impractical for small local operations, and only materials with sufficient economic value can justify the cost of the separation process.

To overcome the sorting problem, desktop recycling and 3D printing could use a predictable source of plastic, such as PET bottles, but the best candidates for such recycling are also the most ubiquitously recycled in municipal waste streams already. Predictable waste streams from Extended Producer Responsibility (EPR) programmes are generally highly mixed materials; they will be equally hard to sort for 3D printing as for other manufacturing methods today. Today, most companies participating in EPR programmes, such as Waste Electrical and Electronic Equipment recycling (WEEE), rely on third parties to perform their material recycling, because producing high-quality raw materials from recovered products is a specialised task with economies of scale (Mayers, 2007). 3D printing does not change these economics, except perhaps to allow more expensive materials through reduced labour costs.

Home desktop recycling and printing could be a closed-loop system of manufacturing single-material objects and then grinding them into raw material when the user tires of them, but this would require people to tire of old objects at the same rate at which they print new ones, and to make all objects in the same single type and colour of plastic. Alternatively, it would require users to hold their own personal storehouse of different plastic spools. It is unrealistic to expect such scenarios on a large scale. Such capability has always existed in the clothing sector, and while home recycling of clothes into fabric for new homemade clothes was widespread 100 years ago, it is at best a hobbyist market today. Purchasing new clothing is easier than sewing clothes at home, and clothing is inexpensive enough that the money saved by recycling fabric fails to equal the value of time spent designing and creating clothing. Just as with home sewing, some hobbyists will 3D print their own parts at home for the joy of making them, but it will be a small niche.

Besides these barriers to recycling, many 3D printing materials are difficult or impossible to recycle. The printing processes offering the highest quality, and thus most often entering commercial manufacturing, are generally the least capable of using recycled material. All photopolymer printers (such as SLA, PolyJet, inkjet, and DLP) use non-reversible chemical processes, thus the materials are inherently non-recyclable. Metal printers raise difficulties for recycling due to tight quality tolerances for input materials, though it is not impossible. Unused metal powders in SLM, DMLS, and other processes degrade in quality each time they are reused (Slotwinski et al., 2014), and such powder is currently not produced from recycled metal because it requires extremely high purity (Yadav, Dirstine and Pfaffenbach, 2004). FDM printers are the only widespread printer type that use recycled materials with ease.

Recycling examples and promise

Multiple researchers, hobbyists, and start-ups have 3D printed with recycled materials. Desktop devices such as Filabot (Biggs, 2013) and Extrusionbot (Sevenson, 2014) grind waste plastic into granules and extrude it into filament for FDM printers. Such processes may even be lower energy than municipal recycling (Kreiger et al., 2013). One group measured a desktop recycler's energy use to be roughly 38 megajoules per kilogramme (MJ/kg) of recycled ABS plastic (Baechler DeVuono and Pearce, 2013), which is at the low end of commercial recyclers' energy use (38 MJ/kg to 43 MJ/kg) (Possamai, 2007). As described above, 3D printing generally causes much more energy use per part than injection-moulding, so desktop recycling for 3D printing is unlikely to be a net environmental benefit even if the recycling

phase is low-energy, but future technologies could change this. On the industrial scale, two architectural start-ups print with recycled material – as mentioned before. KamerMaker uses recycled plastic; it also eliminates other building materials such as sheetrock and waterproofing membrane. WinSun uses recycled glass and other concrete aggregate in cement, and metal powder printers (e.g. SLM, SLS and DMLS) can reuse unmelted powder for non-aerospace applications.

Printers that bind particles with an adhesive (such as WinSun's) can be quite tolerant of diverse materials, ameliorating the sorting problem. The disadvantage of such methods is that they down-cycle material into a lower-quality mixture which cannot be expected to have high-performance physical properties. However, this has been acceptable for decades in many industry sectors, such as recycled plastic decking or other architectural materials. There is not yet enough data to predict whether 3D printing is more economical or higher quality than existing forms of mixed plastic recycling.

3D printing may theoretically enable increased recycling by reducing the number of parts in a product and reducing the number of different materials, through complex geometries and tunable materials. This is speculation, but is based on well-accepted general principles. First, a core principle of designing products for recyclability is to reduce the number of parts used, to save labour cost of disassembly (Possamai, 2007). 3D printing can create highly complex parts, allowing it to replace many simple parts with a single complex part. Second, another core recyclability principle is to reduce the number of different materials in order to reduce sorting (Dahmus and Gutowski, 2007; Possamai, 2007). Advanced 3D printing can include geometric variations that can somewhat vary the flexibility, strength, and other properties of a part from one location to another, despite it being the same material throughout. Some printing processes, such as WBDF, even allow tunable material properties depending on the printing process. Thus multiple materials could in theory be replaced by single materials in some cases.

Composting versus recycling

In the long term, composting could be another route to a circular economy, as it can accommodate mixed materials that are inseparable. Recycling of 3D printed parts appears unlikely to become more widespread in the future because, as described before, more printers will print multiple materials simultaneously as technology advances. This is useful economically, but destroys recyclability. Compostable materials allow biological recycling regardless of different aesthetic, physical, and electrical properties. This need not limit the material palette available to designers and engineers, as nature demonstrates a vast array of physical and chemical properties in the materials comprising plants and animals, all of which are compostable. On the other hand, there are also a number of limitations and risks to compostable materials, which may result in making incineration a more attractive treatment option. For example, biodegradable plastics, if mixed together with conventional plastic, can disrupt established and well-functioning plastic recycling, as well as encourage littering (because consumers assume they will degrade quickly).

Many 3D-printable materials can already be composted in some municipal-scale facilities: PLA bioplastic, composites of wood fibre and bioplastic, starch, even biodegradable conductive composites that could be used as wiring (Van Wijk and Van Wijk, 2015; McDonald, 2016; Ray, 2013; Kilner, 1993). 3D printed food is obviously compostable, though not structural enough for most product applications. As mentioned above, MIT's WBDF material is both structural and dissolves in water in minutes. The University of Wageningen and designer

Eric Klarenbeek collaborated to 3D print furniture out of oyster mushroom mycelium with a PLA shell (Fairs, 2013). Ecovative has sold a similar mycelium-based material for packaging since 2007, which biodegrades in 30 days by ASTM D6400 standards (Ecovative, N.D.). While no commercially available structural 3D printing materials compost so easily, focused research and development could create them.

Some compostable bioplastics, such as PLA, are already in widespread use and are already more sustainable to produce than petroleum-based plastics, both in terms of embodied energy and toxins. PLA has much less embodied energy than most plastics (~27 MJ/kg in 2007) (Vink, 2007), with Dow aiming to reduce it to 7 MJ/kg (Vink et al., 2003), as opposed to the ~40 MJ/kg for recycled ABS listed earlier, or ~100 MJ/kg for virgin ABS) (Granta Design, 2009). PLA has also been shown to emit fewer toxic fumes than ABS while FDM printing (Stephens et al., 2013). However, to be composted, PLA needs municipal-scale facilities which reach high temperatures; these are not common globally today, and thus PLA is not yet compostable in most cities today. In the long term, such compost facilities are likely to become as common, or even more common, than recycling facilities because their indifference to sorting makes them less expensive per unit of waste diverted (roughly USD 50/tonne) (Renkow and Rubin, 1998) rather than USD 75/tonne for recycling) (Bohm et al., 2010). Even today, more cities in the United States have municipal compost services than services that recycle ABS plastic kerb-side, as municipal recycling optimises for the highest-volume plastics such as PET.

Local-scale plastic recycling for 3D printing may perhaps be more successful in developing countries than in developed countries, due to limited infrastructure and differing costs of labour versus materials. Developing countries often lack municipal recycling systems, leaving the economic niche unfilled. Also, materials are more expensive compared to labour than in developed countries, so there is more incentive to recover and sort materials. Indeed, whole neighbourhoods make their living hand-sorting open dumps in some places today (Gill, 2009). Thus composting may not have the same cost advantage over recycling as in developed countries. Finally, low-income consumers often have lower quality requirements for goods if they are inexpensive enough, so it is easier to meet needs with the FDM technology that enables desktop plastic recycling into 3D printing. However, these trends may not be strong enough to favour recycling over composting even in developing countries.

Legacy product repair

The most important way that 3D printing could encourage material reuse is not through recycling, but through repair. Many legacy products are discarded because a single component breaks and there is no longer a supply chain to replace it. These components are often single-material plastic or metal parts, which 3D printing is already well suited to replace. The primary barrier to ubiquitous printing of replacement parts is intellectual property (IP): both the accessibility to end users of 3D models for printing, and the legal right to print models that are available. Some websites such as Thingiverse are already open repositories for free downloads of 3D models to print replacement parts for dishwashers, refrigerators, bicycle accessories, and more. The 3D models are legally ambiguous, arguably not violating IP laws because they are reverse-engineered, but challenges came as early as 2011 (Coetzee, 2011). Businesses may learn to monetise such sites for IP rights, just as Napster's illegal music sharing evolved into paid subscription services such as Pandora or Spotify.

Policy could easily encourage 3D printing for repair, as several companies are already in a position to provide this service, including billing and royalty payments. It is merely a question of legal rights and contracts. Thingiverse could charge a fee for users downloading the file to print at home, and send royalties to the original product manufacturer. Companies such as Shapeways, which provide a web-based interface to mail-order 3D printed parts, do not even require the end user to have a printer in their home. It is unclear whether such markets will be large enough to avoid significant amounts of discarded products, as repairs require not only parts, but labour – often skilled labour. Still, it is a worthwhile experiment, as it requires no new technology or investment, only legal clarity for existing entities to engage in such practices.

Saving use-phase energy

It may be that 3D printing's most important contribution to sustainability will come not from manufacturing impacts, but from saving energy in the use-phase of products' lives. This is speculation, as such savings may only accrue in aerospace, automotive, or other industries where use-phase energy impacts dominate the entire product life cycle, and where such energy use depends heavily on the mass of material in the product.

The higher complexity of manufacturing enabled by 3D printing can allow for lower-mass parts, which can save fuel in transportation products. For example, General Electric's 3D printed parts for the jet engine described earlier reduce weight, improving fuel efficiency by 15% (Beyer, 2014). Even if the manufacturing of the parts themselves has a greater environmental impact than previous methods such as machining or welding, these large use-phase energy savings can easily overcome increases in the manufacturing phase. Such weight savings would also reduce lifetime impacts of trucking and cars, but would not reduce impacts for other product categories, such as consumer electronics or buildings. However, there are other potential routes for use-phase energy reduction.

The higher complexity enabled by 3D printing can also improve the efficiency of fluid flow and heat transfer for some systems. For example, the SpaceX SuperDraco engine achieves more efficient fuel combustion by having its "regenerative cooling" fluid channels within the walls of the combustion chamber, rather than welded to the outside, as was required for previous manufacturing methods (Post, 2014; Dankhoff, 1963). Use-phase energy efficiency may even be enabled for other sectors, such as architecture. Roughly 90% of an average building's lifetime environmental impact is from its energy use (Faludi, Lepech and Loisos, 2012), and air leaks through gaps in construction are a major culprit (Liaukus, 2014), especially at corners and joints. Though it has not yet been demonstrated, in theory printing all of a building's walls as one continuous piece could help avoid such leaks.

Social benefits and the need for green 3D printing to scale

One of 3D printing's sustainability impacts may be social, not environmental. Economic empowerment is a significant part of sustainability. 3D printing empowers small businesses and others with limited access to capital by radically reducing economic barriers to entry into manufacturing. Anyone with a moderate-quality computer and CAD software can create 3D models for parts, then have the parts printed in high quality without the expense of tooling a mass-manufacturing line. Printing is often even less expensive than traditional forms of prototyping, such as machining (Beyer, 2014). Such empowerment of small businesses could help to reduce income inequality in developed countries, and help developing countries to industrialise.

The widespread replacement of injection-moulding for mass manufacturing would probably be an environmental problem with current 3D printers, but the replacement of machining for hollow-shell parts would probably bring about environmental benefits if two conditions are met: greatly reducing energy use per part printed, and reducing the embodied impacts of printing materials. These goals can be achieved through many strategies, e.g. maximising utilisation, eliminating toxic chemistry and reducing material waste. Table 5.2 lists some specific strategies for these goals by printer type.

Table 5.2. **Strategies for more sustainable 3D printing by printer type**

Printer type	Strategies to minimise material impacts	Strategies to minimise printing energy	Strategies to minimise idle energy
Photopolymer	Eliminate toxic chemistry Develop compostable biopolymers Minimise support material Tune material properties through printing process	Print more parts simultaneously Minimise print time Design for efficiency	Share printers to minimise idle time Low-power idle mode
Inkjet	Expand/improve compostable biopolymers Tune material properties through printing process		
Metal laser sinter/melting	Produce powders from recycled metals Improve reusability of metal powder Minimise support material Tune material properties through printing process		
Extrusion	Expand/improve compostable biopolymers Hollow parts and minimal support material Tune material properties through printing process	Chemically solidify materials rather than melting thermoplastics Hollow parts and minimal support material Minimise print time Design for efficiency	

Source: Authors' analysis.

Table 5.2 shows that because 3D printers vary so much in their design and operation, few sustainability strategies apply to all printer types equally. Reducing energy use per part made is the top priority for sustainability in 3D printing, but it can require different strategies for different printer types. One energy-reduction strategy common to all printers is minimising idle energy. Idle energy can be reduced both by having printers automatically enter low-power sleep states when they finish printing, and/or by sharing fewer printers among more users. Also common to all printers is simply designing them for energy efficiency. The relative low cost of electricity today means that many printers lack simple energy-saving features such as insulation around heated components. The final energy-reduction strategy common to all printers is reducing print time. Many 3D printers use the majority of their electricity to simply keep support systems running, the additional power for printing is often small (Faludi et al., 2015b). Thus more parts could probably be printed with less energy per part if print times were reduced, even if more print heads, lasers, etc. were required.

A material impact reduction strategy common to all printers is tuning material properties, as (in theory) all types of 3D printers should enable this in the future, albeit by different means. Much of the table lists technology-specific strategies. For extrusion printers, energy savings correlate to material savings, so hollowing parts and minimising support material save both material and energy. Extrusion printers can also significantly reduce energy use by chemical solidification rather than melting plastics. Photopolymer, inkjet, and laser sintering machines can reduce energy per part by maximising the number of parts per print, because they can print several parts using almost the same energy as

printing a single part, regardless of material use. For material impact reduction, most printers can minimise support material, but inkjet printers do not generally need support material, so it is not a priority for them. Reducing toxicity is a higher priority for photopolymer systems than others because non-toxic materials already exist for other printer types. Compostable biopolymers are one option for photopolymer printers because photopolymers are inherently unrecyclable, and incineration with energy recovery is another. Compostability is already possible for some inkjet and extrusion printer materials, though today options are limited. Development is required to expand commercially available choices and improve physical performance of such materials, if they can be produced at competitive cost and ways can be found to deal with their potential to disrupt existing recycling systems. Metals are not generally compostable, so metal sinterers should improve material recyclability, both in terms of powder reuse and producing powder from recycled metal.

An example of 3D printing's potential is the Solar Sinter by Markus Kayser. It functions similarly to SLS, but instead of sintering plastic or metal powder with a laser, it uses a large Fresnel lens to sinter sand into glass with the heat of the sun. Its motors and electronics are powered by solar panels and the sand used is non-toxic, abundant, local, and requires no energy-intensive processing before use in the printer. The Solar Sinter was merely a demonstration project, probably not practical for industry, but it can serve as a beacon for what is possible. Even without such extreme measures, some commercial 3D printers today are capable of printing non-toxic, abundant, renewable, compostable materials with low-energy printing processes – close to the ideal for sustainable manufacturing. For example, inkjet printing in salt or sawdust, or MIT's WBDF.

Policy priorities and mechanisms to accomplish environmental policy goals

Policy mechanisms

This section outlines the priority areas to improve the environmental implications of 3D printing. Table 5.3 highlights some of these areas. The table lists high, medium and low-priority goals for printer design, materials, printer operation, IP and use-phase energy efficiency. These priorities serve the goals of minimising energy use and waste, as well as transitioning to materials which are non-toxic, abundant, renewable, and low-embodied-energy, with useful end-of-life.

The 3D printing industry is at an inflection point, meaning that interventions implemented now rather than a few years from now would have greater impact. Some possible interventions include banning specific practices, taxes, subsidies, certification systems (eco-labels), and preferential purchasing programmes. Interventions in other industries could also fix impacts in the 3D printing industry: since its largest impact is from the electricity to print parts, converting national electrical grids to 100% renewables (as is already being done in some countries) could cut printing impacts by perhaps 75%. Of course, such measures would also improve other electricity-intensive manufacturing methods. 3D printing industry interventions should primarily target printer design, materials, and operation. As mentioned above, interventions encouraging 3D printing of parts in industries such as aerospace in order to reduce use-phase energy demand should target those industries, not the printing industry, because 3D printing is just one possible means to improved fuel efficiency. The following sections consider several policy mechanisms for directly influencing the 3D printing industry.

Table 5.3. **Priorities for improving environmental impacts of 3D printing**

Focus area	High priority	Medium priority	Low priority
Printer design	**1. Design for minimal idle time (ease of sharing, minimal set-up/clean-up time)** High leverage and simple to implement. **2. Automatic low-power standby** High leverage and simple to implement.	**1. Low-energy printing process (chemical bonding, not melting)** Moderate to high leverage, but requires significant investment and must be combined with energy-efficient equipment systems. **2. Energy-efficient equipment systems (insulation, motors, electronics)** High leverage, but requires significant investment.	**Design software and hardware to minimise material use and waste** High leverage, but market incentives already exert pressure in this direction.
Printing materials	**1. Non-toxic, compostable photopolymers for SLA, DLP, PolyJet, CLIP printers** High leverage and large installed base of photopolymer printers. **2. Improved physical performance/print quality/compostability for existing biopolymers in low-energy print processes** Commercialising existing materials requires less investment than developing new materials.	**Chemical bonding (not melting) of compostable biopolymers, such as MIT's WBDF, for extrusion printers** High leverage, but requires replacing or retrofitting existing extrusion printers (more expensive than simply replacing chemicals in photopolymer printers).	**1. Tunable material properties through printing process, for all printers** Leverage uncertain, still experimental. Could simplify recycling, composting, and toxicity screening, but requires significant investment. **2. Infinitely reusable metal powders produced from recycled material** Probably lower leverage than reducing energy use, and probably requires significant investment.
Printer operations	**1. Sharing printers for more utilisation of fewer machines** High leverage and simple to implement. **2. Optimal bed packing for photopolymer, inkjet, and laser sintering printers** High leverage and simple to implement.	**Minimising support material for all printers** Leverage varies by printer type; implementation can be inexpensive (e.g. improving software algorithms) or expensive (e.g. improving hardware capabilities).	**1. Avoiding failed prints** Leverage varies by application; already strongly incentivised by existing market forces. **2. Hollowing parts for extrusion printers** Leverage varies by application; already strongly incentivised by existing market forces.
IP	**1. Rights for third parties to print replacement parts for products (paying reasonable royalties as needed)** Unclear leverage, but requires only simple legal action with precedent in other industries. No technology development required.		

Source: Authors' analysis.

Bans and taxes

Bans of particular 3D printing-specific practices would probably be unproductive, because of redundancy with regard to existing bans and the difficulty of measuring performance. Negative environmental impacts that are easily measured are largely covered by existing bans. For example, photopolymers and other chemicals used in printing are often somewhat hazardous, as mentioned earlier, but no more so than many other manufacturing processes. All industry chemicals must already comply with existing chemical bans such as the European Union's Restriction of Hazardous Substances Directive (RoHS) and limits set by the Registration, Evaluation, Authorisation and Restriction of Chemicals regulation (REACH) in Europe. While there are strong arguments for the necessity of stricter chemical regulations, any chemical classes used in 3D printing that legislators wish to ban should probably be banned throughout industry, not just for 3D printing.

The impacts of 3D printing can also be difficult to effectively measure at the printer level. Even parts printed with large amounts of energy in the manufacturing phase may reduce use-phase impacts of the products they are used in, such that the total environmental impact is much lower. For example, in aerospace or ground vehicles light weighting improves fuel efficiency. Thus a ban on printers above a certain energy intensity

per part printed could inadvertently ban the production of environmentally beneficial parts. Besides these factors, bans are often seen by industry as more of a threat than other policy measures such as voluntary certification systems, and thus meet more political resistance.

Taxes on 3D printing-specific practices would also probably be unproductive, for the same reasons listed for bans. While carbon taxes can be effective for incentivising energy reduction in manufacturing (Larsen and Nesbakken, 1997; Veugelers, 2012), such taxes should not be limited to 3D printing. Instead, they should apply to whole state economies to provide maximum effectiveness and cause the least shifting of impacts from one industry to another. If industry-wide taxes are considered, the one most relevant to 3D printing would be a carbon tax, as the largest single impact of 3D printing is usually emissions from fossil-fuel-derived electricity.

Grants and investments

Government agencies have spent hundreds of millions of dollars on 3D printing, both in research and technology adoption. Focusing government grants and investments on sustainability could significantly move the industry. For example, MIT's Center for Bits and Atoms was founded by a USD 13 million National Science Foundation grant in 2001. In 2014 Spain granted Hewlett Packard over EUR 21 million for 3D printing research and development. In 2013 and 2014, the UK government granted over GBP 60 million to 3D printing projects. The People's Republic of China (hereafter "China") is investing CNY 1.5 billion (USD 245 million) on the industry over seven years. In 2014, US President Obama pledged that "11 agencies that collectively grant over USD 2.5 billion annually to small businesses across the country… are committing to leverage the programs to support maker innovations".

Overall, these grants have not targeted sustainability concerns. However, if they did, the major funding involved could certainly push 3D printing towards sustainability, similar to investment in clean energy industries (Veugelers, 2012).

University grants or discounts can be particularly high leverage to build a market share for environmentally preferable printers. Students who learn their trade using a certain technology or brand of product often prefer that product throughout subsequent decades of their careers, through the persuasiveness of commitment (Cialdini, 1993). This tactic is used by firms as large as Microsoft, Autodesk, and Apple. Universities have also received tens of millions of dollars in government grants for 3D printing. If such funding were contingent on the 3D printers meeting a certain green label standard, or contingent on research being directed towards sustainability, it would probably have great leverage. In addition, university students tend to be environmentally aware, so universities would probably be easier to persuade to follow such strictures than national governments.

Investments in green materials for 3D printing would probably also benefit other industries, such as injection-moulding or other plastic forming. PLA bioplastic can be injection-moulded as well as 3D printed, and new materials might also be usable in other manufacturing processes. Compostable biopolymers and tunable materials may again have more advantages here than recycling materials, because different manufacturing methods often require different material properties.

Preferred purchasing programmes

Environmentally responsible procurement policies can move markets, but they require credible standards for their preferences. The US and other governments' policies,

e.g. purchasing only EnergyStar certified computers, have moved markets because governments are very big customers. However, Li and Geiser concluded that an environmentally preferable purchasing policy cannot be achieved alone, and depends on other independently functioning policy instruments such as ecolabelling (Li and Geiser, 2005) In order to avoid cronyism or the appearance thereof, and to integrate well with other policies, preferential purchasing of 3D printers should be contingent on objective measures, such as third-party sustainability certification systems (eco-labels).

Voluntary labelling systems

Voluntary ecolabelling is probably a necessary, but not sufficient, condition for shifting the 3D printing industry towards sustainability. The 2009 RAM requested "government-driven incentives for development of sustainability metrics" (Bourell, Leu and Rosen, 2009). Sustainability certifications can move markets powerfully – over three billion square feet of buildings have been Leadership in Energy and Environmental Design (LEED) certified (USGBC, 2008) and over 100 million EnergyStar certified products are sold per year in the United States alone (Banerjee and Solomon, 2003). However, consumers care much less about sustainability than they do about cost, quality, and user experience in many markets (Ottman, Stafford and Hartman, 2006). 3D printing is currently one of these markets. Still, voluntary certifications can become powerful tools with the addition of preferential procurement policies. The US federal government requires all new buildings to be LEED certifiable, which has had "a huge impact on national construction trends" (Nelson, 2007). The voluntary label becomes the threshold for mandatory (or preferential) policies.

Voluntary eco-labels for 3D printers should use multiple criteria and have multiple grades of certification, similar to the Electronic Product Environmental Assessment Tool (EPEAT), LEED, and Cradle to Cradle labels. Multiple criteria encourage industry to consider sustainability more holistically, rather than making unfortunate substitutions of one environmental impact for another. Multiple grades of certification encourage both laggards and leaders to improve, while single-threshold certifications only drive improvement to that single level. Certification criteria should include the various policy priorities listed above for printer design, materials, and operation. For example, the certification system could encourage energy efficiency by scoring printers according to their energy use per gramme of printed model material. Because of the complexities of 3D printing conditions, such scoring would probably depend on a set of benchmark geometry parts, part orientation, bed packing, and other factors. Separate certifications might be developed for 3D printer designers and 3D printer operators. For example, printer operators most determine the percentage of bed packing and the percentage of time a printer is printing versus idle, while printer designers most determine what materials a printer may use.

Cases where the environmental impacts of printing are high, but where the parts reduce use-phase energy enough to compensate, will probably be too difficult to predict or measure in a certification system for printer design or operation. Instead of attempting to write such scenarios into a 3D printer ecolabel, these circumstances should be dealt with by environmental standards related to the final product instead, such as fuel efficiency standards for vehicles. If voluntary 3D printing eco-labels are used by government procurement policies, such policies should allow exemptions for these cases.

Conclusions

3D printing could dramatically shift industrial manufacturing methods away from traditional technologies and widen access to the means of production of manufactured goods. Additive manufacturing will also pose potential benefits and drawbacks for environmental sustainability if it is scaled up across multiple industries in the next decade. Widespread 3D printing's sustainability will probably be a complex set of trade-offs compared to other manufacturing methods – beneficial in many ways, but negative in others. It already reduces manufacturing-phase environmental impacts in some applications, such as certain types of prototyping or small-run production, and reduces use-phase environmental impacts in some applications, such as saving weight in aerospace parts. However, sustainability has not been a priority for all but a few outliers in the 3D printing industry, and most standard printers operating in typical conditions cause higher impacts per part than injection-moulding plastic at high volumes.

Environmental impacts of present manufacturing technologies are highly varied and dependent on the parts being produced. Future studies should compare 3D printing to each major technology they replace, for each relevant product type and material. In the absence of such studies, this chapter examines two technologies: machining and injection-moulding. These were chosen to represent two ends of the spectrum, from single-unit prototyping to mass manufacturing. Even in these limited circumstances, the environmental impacts of 3D printing processes vary too widely to make unequivocal declarations. For "typical" circumstances, life-cycle assessments show that 3D printing a hollow-shell part causes lower environmental impacts per part than machining the same part from a block of plastic or metal, but 3D printing causes higher environmental impacts per part than injection-moulding the same part in mass quantities. However, these results depend on printer type, utilisation, part orientation, part geometry, and other factors to such a degree that they are often untrue.

Typically, environmental impacts of 3D printing are primarily due to energy use. Secondarily, they are due to toxicity and resources embodied in printing materials and finally are also caused by material waste, with small percentages due to production of the printers themselves. Some experimental systems already have far lower environmental impacts per part than injection-moulding – perhaps 70% lower in some circumstances. However, industry is not trending towards such systems, but rather towards systems with much higher (double, quintuple, or larger) impacts than injection-moulding. Thus, policy should encourage lower-impact technologies.

Expansion of 3D printing into other industries depends on its near-future evolution in print time, cost, quality, size, and material choice. The largest factor driving and limiting its expansion is the cost curve of switching from mass-manufacturing methods to 3D printing. This curve is not linear but hyperbolic. Thus it is rapidly penetrating high-cost, low-volume industries such as prototyping, automotive tooling, aerospace, and some medical devices; it will more slowly penetrate moderate-cost, moderate-volume industries, and low-cost, high-volume industries will not switch to 3D printing for decades, if ever. The expansion of 3D printing will have consequences for economies outside of the manufacturing sector as well. Its automation will further reduce employment in manufacturing, requiring shifts to other employment sectors, but it will democratise production, encouraging entrepreneurship. Its main benefit to developing nations is unlikely to be in helping the poorest of the poor in rural conditions. Instead, it will more likely be in helping urban entrepreneurs with little access to

capital start small-scale manufacturing and self-fund later expansion into low-cost mass manufacturing.

As previously described, 3D printing aligns some economic incentives with environmental impacts, making material use expensive while complexity is almost free, which incentivises the reduction of material use and waste through sophisticated design. In addition, printer operators have an economic incentive to reduce printing energy by reducing print time. However, printer designers have no such incentive. The final alignment of economic incentives is the enabling of lean manufacturing by eliminating economies of scale that encourage overproduction. However, a counter-trend is that easy desktop 3D printing will encourage some overproduction similar to (though much less severe than) that which easy desktop publishing caused for paper use. Besides these economic incentives, 3D printing enables material experimentation, which can encourage the use of more sustainable materials, and can also drive large reductions of energy use by printing via chemical processes instead of melting. However, market incentives for sustainable materials and low-energy printing processes are weak to non-existent.

- First, 3D printing can align economic incentives with environmental impacts, encouraging less material and energy use through more sophisticated design. Part of this alignment of incentives is the enabling of lean production.
- Second, 3D printing can enable more sustainable material choices because:
  - It allows many materials to achieve the ease of shaping previously enjoyed only by plastics.
  - It lowers barriers to switching between materials by reducing economies of scale. It can enable fewer chemical ingredients to produce more variation in material properties by varying printing processes.
  - Its labour cost reduction can allow for the use of more expensive materials while still lowering total production cost.
- Third, 3D printed parts can improve use-phase impacts of some products, allowing a reduction of total lifetime impacts even if manufacturing-phase impacts are higher. This can happen in two ways:
  - By printing replacement parts for legacy products that would otherwise be discarded due to lack of a supply chain for repair parts.
  - By reducing weight in a vehicle or otherwise improving a product's use-phase energy efficiency. Such energy savings can be quite large compared to manufacturing impacts, especially in the aerospace industry.

Finally, 3D printing may have social benefits by democratising production. For these potential benefits to scale, the chapter identifies specific factors that policies should target for different printing technologies.

3D printing's environmental benefits are not a foregone conclusion, they must be encouraged. For example, 3D printing does not inherently encourage material recycling; many printing materials and methods actively discourage it. While experimenters have created desktop plastic recycling for desktop printers, this is unlikely to scale, due to the difficulty of sorting materials. Market forces may favour compostable materials in the long run, especially as printers trend towards printing multiple materials in the same part. Many printable compostable materials already exist today. On the other hand, incinerating

these materials and recovering the energy that is contained in them may be another option that avoids some of the issues that can result from the use of compostable plastics.

3D printing can encourage efficient material and energy use through lean production. The use of recyclable materials could also be a policy objective. Another very practical environmental benefit would be to advocate for the legality of printing spare parts for existing products, to lengthen the lives of products no longer supported by their original manufacturers.

The negative environmental impacts of 3D printing are largely due to energy use, toxicity and material choice. Technologies exist today that can radically reduce 3D printing's impacts – to roughly 70% less according to the ReCiPe method for life-cycle impact assessment (LCIA) per part than injection-moulding – through low-energy printing of abundant, non-toxic, renewable, compostable ingredients, with tunable physical properties. Preliminary findings suggest that the net impact on the environment would depend upon a number of variables including printer type, utilisation, part orientation, part geometry, and other factors. That said, 3D printing has great potential for environmental sustainability.

To encourage sustainability in 3D printing, policy interventions should primarily encourage low-energy printing processes and low-impact materials with useful end-of-life. Some ways in which printer design and operation can minimise energy use per part are by using chemical processes rather than melting material, automatically switching to low-power states when idle, and by maximising utilisation, both sharing fewer printers among more users and, for some printer types, printing more parts simultaneously. Low-impact materials refer to materials that are non-toxic, abundant, renewable, low-embodied-energy, and enable a useful end-of-life. Some ways in which printers can minimise material impacts are by using compostable biopolymers with high print quality, and as mentioned above, by chemically bonding rather than being melted. Printer design and operation can also reduce waste by minimising support material, hollowing parts, and avoiding failed prints. In addition to these priorities, policy should enable 3D printing of repair parts for legacy products without existing repair supply chains, by clearing legal intellectual property barriers.

Policy mechanisms to achieve these priorities should include targeting financial grants or investments (either existing programmes or new funds) to commercialise research in these directions. They could also include a voluntary certification system to label 3D printers with different grades of sustainability across multiple characteristics, similar to EPEAT, Cradle to Cradle, or LEED certifications. This voluntary certification system could be combined with preferential purchasing programmes by governments and other large institutions.

Expansion of 3D printing into other industries depends on its near-future evolution in print time, cost, quality, size, and material choice. The largest factor driving and limiting its expansion is the cost curve of switching from mass-manufacturing methods to 3D printing. This curve is not linear but hyperbolic. Thus it is rapidly penetrating high-cost, low-volume industries such as prototyping, automotive tooling, aerospace, and some medical devices; it will more slowly penetrate moderate-cost, moderate-volume industries, and low-cost, high-volume industries will not switch to 3D printing for decades, if ever. The expansion of 3D printing will have consequences for economies outside of the manufacturing sector as well. It also has the potential to economically empower small businesses, but could also eliminate jobs in both developed and developing countries. Automation will further reduce employment in manufacturing, requiring shifts to other employment sectors, but it will

democratise production, encouraging entrepreneurship. Its main benefit to developing nations is unlikely to be in helping the poorest of the poor in rural conditions. Instead, it will more likely be in helping urban entrepreneurs with little access to capital start small-scale manufacturing and self-fund later expansion into low-cost mass manufacturing.

3D printing's potential for environmental sustainability is high. Two of the most touted sustainability benefits, eliminating waste and eliminating transportation, are largely fallacies; however, there are many sustainability benefits that could be quite real, if pursued.

While widespread 3D printing would not automatically be an environmental benefit as practised today, technologies already exist that, if brought from the industry's fringes to its status quo, could dramatically shift manufacturing towards more sustainable production. Today's rapid industry growth may set the path for decades to come, so policy interventions now could have a great deal of leverage.

In its current state, 3D printing is not a net environmental positive, but must rather be guided by strong environmentally focused policies from the fringes of the manufacturing industry to the mainstream while ensuring that it is not singled out among other industries. Since the industry is at a crossroads, well-placed incentives today might establish beneficial technologies for decades to come, making widespread 3D printing an important part of a more sustainable future.

Note

1. Machining as such is not mentioned in BEA input-output tables (BEA, 2014). This estimate considers the weigh that a range of machining-related sectors (Machine shops; Turned product and screw, nut, and bolt manufacturing; Metal cutting and forming machine tool manufacturing; Cutting and machine tool accessory, rolling mill, and other metalworking machinery manufacturing; Hardware manufacturing; Other fabricated metal manufacturing) have on the total value of the manufacturing sector. As in 2007 the manufacturing sector had a total value of USD 914 819, machining-related activities represented about 0.05% of this figure (BEA, 2014).

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The Next Production Revolution
Implications for Governments and Business
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PART I

Chapter 6

Revolutionising product design and performance with materials innovation

by
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Increasing the rate of discovery and development of new and improved materials is key to enhancing product development and facilitating mass customisation based on emerging technologies such as 3D printing. Acceleration of materials discovery and development has been enabled by advances along multiple fronts, including capabilities of scientific instrumentation, high performance computing combined with more predictive computational methods for material structure and properties, and data analytics. Historically it has taken 15 to 20 years from laboratory discovery of new materials to their deployment in products. Systematic methods for accelerated materials discovery and development are still in early stages in the new digital era. Prospects are bright for realising a materials innovation ecosystem necessary to integrate new materials with digital manufacturing technologies to achieve new product functionality. A range of initiatives, gaps, and key policy issues to be addressed are discussed in this chapter.

Introduction

Historically, the process of discovering new materials and developing them to meet market demands has been laborious, iterative, and intuitive, driven by perception of consumer needs for new products or existing potential product improvements. The process has conventionally involved the following steps: i) generate a new or improved material concept; ii) realise this material via "Edisonian" trial and error methods in the lab; iii) measure desired property sets; and iv) repeat, improve, and refine. Unfortunately, the path to commercial viability with this schema has typically taken 15 to 20 years, with wide-scale acceptance in commercial applications requiring an additional 20 years or more, as outlined in the US Materials Genome Initiative (MGI) (Kalil and Wadia, 2011; Holdren, 2014).

In the next production revolution, engineers will concurrently design the product and its constituent materials (McDowell, 2007; Teresko, 2008), as shown in Figure 6.1. Hierarchical levels of material structure from atomic scale through interfaces of multiple phases, upward to the part level are considered, effectively treating levels of material structure and associated responses as subsystems. In Figure 6.1, the typical organisational separation of processing materials and certifying their properties in materials development is distinguished from that of materials selection in design of product systems (inset lower right). Conventionally, materials have been developed in the supply chain to meet property requirements of systems designers working with original equipment manufacturers (OEMs). Designers typically select materials that are suitable for manufacturing products. In the new world of tailoring materials for specific product applications, the linkage between the materials supply chain and OEMs/designers will become much more intimately coupled, and two-way in character, with a focus on tailoring a product-specific hierarchy of material structure as highlighted in Figure 6.1.

Continued 21st-century market punctuations are likely to arise at the intersection of big data and existing infrastructure and technologies, resulting in transformation of everyday means of communication, transport, and commerce. Creation and expansion of new products and even industry sectors can result**.** Accelerated materials discovery and development is about more than just anticipating, developing and addressing consumer demand and offering improved competitive products. New materials hold promise to address many grand challenge problems.

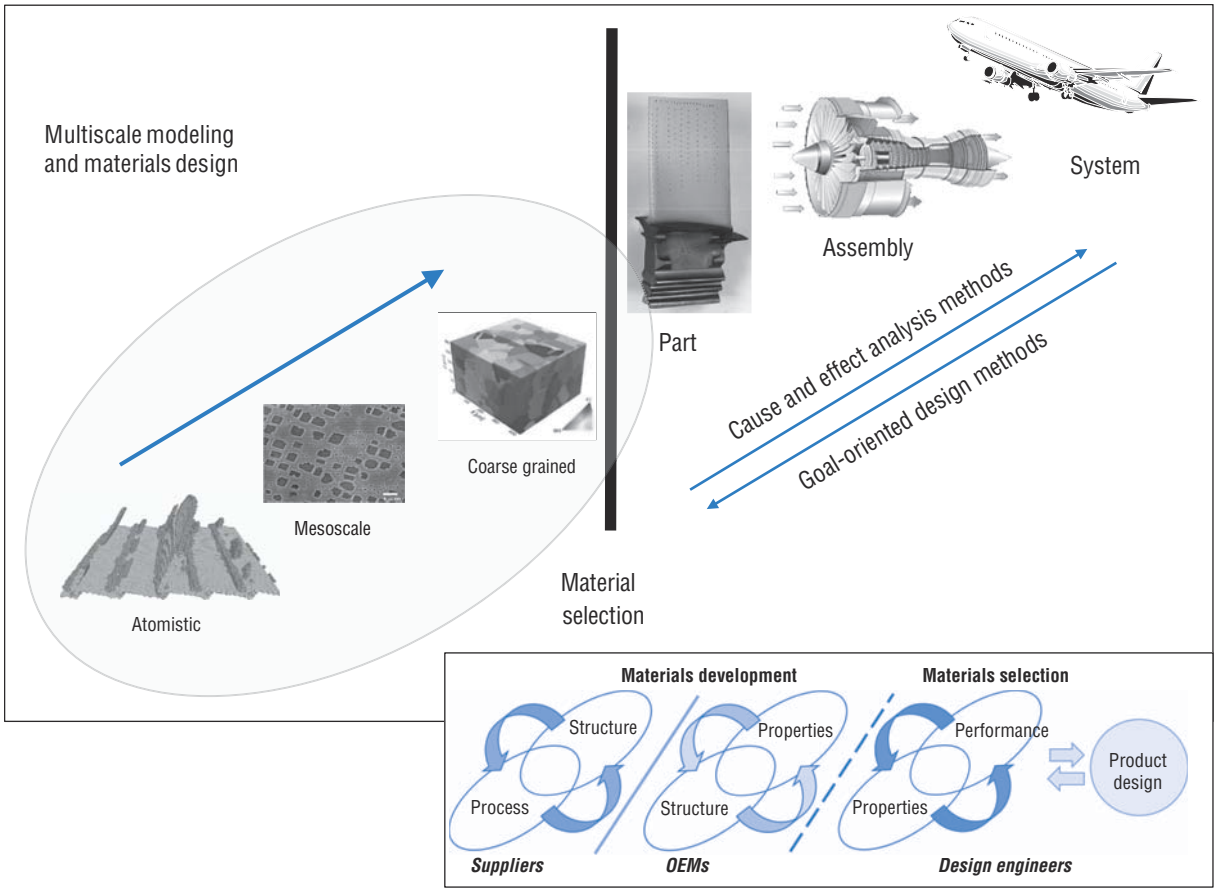
Economies that pursue development and integration of technologies to link materials development with product manufacture can realise benefits if they build a sustainable culture that supports distributed discovery, design and development of materials. Such a culture can support a robust materials innovation ecosystem that cuts across materials suppliers, OEMs, government agencies and labs, and service providers, with universities providing appropriate technical support and future workforce education.

This chapter first elaborates the promise of new materials in the digital age, trends that enable accelerated materials development, and the need for a materials innovation ecosystem to link digital materials and manufacturing. Prior to concluding by outlining

new policy issues and their relation to longstanding policy concerns, the following challenges to realising the promise of cyber-enabled accelerated materials discovery, development and manufacturing can be identified and discussed:

- building the culture of the materials innovation ecosystem
- integrating a digital materials supply chain
- e-collaboration and web agent approaches to distributed materials and manufacturing
- future workforce development
- road mapping and capitalisation of the materials innovation infrastructure.

Figure 6.1. **Concept of concurrent design and bottom-up development of the material to meet top-down systems and product requirements, including manufacture and performance**



Source: Adapted from McDowell, D.L. et al. (2010), *Integrated Design of Multiscale, Multifunctional Materials and Products*.

The promise of new and improved materials

The dawn of the information age has witnessed remarkable increases in workplace efficiency and productivity. The role of automation in manufacturing of goods has increased dramatically in the past few decades, coupled with advances in digital design for manufacture that allow products and processes to be envisioned and considered in the early design stage, reducing time to market. In this new era of digital manufacturing, one can consider both solid geometries and tolerances of complex parts and assemblies prior to

physical manufacture, transmitting information in digital computer-aided design (CAD) files for production. But products are manufactured from materials, and material form, structure and properties have long remained sources of great uncertainty that limit attainment of the broadest vision of digital manufacturing. Important issues persist regarding the predictive knowledge base of properties and characteristics of existing materials, including machinability, surface conditions, interplay of process route and the material structure, distortion and tolerances, residual stresses, and quality of joints between materials within sub-assemblies. The advent of new manufacturing technologies such as additive manufacturing and 3D printing have made these issues more acute and have sharpened the focus on the need for more integration between materials development and manufacturing. Furthermore, there is an important trend: advances in digital manufacturing need not rely on standard, off-the-shelf materials supply catalogues and inventories. Indeed, prospects are bright for rapid development and deployment of new and improved materials that can be integrated with the digital manufacturing workflow and offer superior new product functionality.

Progress in accelerated discovery and development of materials has been enabled by advances along multiple fronts. Advances in scientific instrumentation, such as atom probe tomography, high resolution transmission electron microscopy and x-ray synchrotron techniques allow scientists and engineers to study materials at finer scale and in more detail than ever before. Developments in computational simulation methods and tools for materials have also been critical. However, these advances must be integrated. The application of data science and high-throughput methods to explore complex data correlations and rapidly evaluate candidate materials has emerged within the last decade and is growing explosively. In conjunction with this convergence of high fidelity and high-throughput experiments, computational simulation, data science and informatics, revolutionary breakthroughs are being realised in manufacturing methods that can take advantage of materials customisation. One such breakthrough is 3D printing.

However, systematic methods for materials discovery and development are still in early stages of "catching the wave" of the new digital era. Historically it has taken 15 to 20 years from laboratory discovery of new materials to their deployment in products. This is partly due to the heavy reliance on empiricism in materials development, which has largely been undertaken in a manner that is disconnected from systems design and manufacturing. Moreover, incentives for university research productivity have emphasised quickly moving from one fundamental research advance to the next, rather than translating these findings into applications. Materials development and certification are critical steps in the "valley of death" in translating new materials concepts from the research laboratory into products (Apelian, 2004). Recent progress in the ability to create and manipulate materials will profoundly affect future production of increasingly customised goods and services. Small variations in a material's composition or structure can lead to significant changes of response or may introduce entirely new functions. Today, materials are emerging with properties never seen before, such as ultra-low density materials with densities comparable to that of air, and metal that expands when stretched. New realities are exotic alloys and high-strength lightweight composites – materials that remember their shape, repair themselves or shape-shift to assemble themselves into components, and materials that respond to light and sound (The Economist, 2015). Manipulating microstructure makes it possible to develop materials with properties that vary from point to point in a given part or component as desired.

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

As evidenced by the categories "Stone Age", "Bronze Age", and "Iron Age", advances in civilisation have been closely connected to advances in materials. In the modern era, "ages" tend to overlap and intertwine. We have rapidly progressed from the industrial revolution (the "Machine Age"), in which a wide range of new materials enabled productivity and convenience, to the present Silicon Age, which has facilitated the emergence of ubiquitous computing. Over half of the major technology breakthroughs of the 20th century[1] were in some way enabled by advances in materials, e.g. cars; airframes and gas turbine engines for aircraft; microelectronics; spacecraft; imaging and health technologies; household appliances; laser and fibre optics; nuclear power; and high-performance, lightweight structural materials. The integration of each generation of new materials technology into consumer products such as cellular telephones, computers, appliances, sporting goods, and cars has been accompanied by a trajectory towards commoditisation as development costs are recovered and the marketplace turns to increased competition among suppliers. However, disruptive new technologies are introduced less frequently and serve to "punctuate" the equilibrium markets, providing potential for localised manufacturing that drives rapid change in consumer preferences, competition for economic viability, and eventual diversification of manufacturing necessary to sustain markets as they tend towards stasis. New and improved materials drive market flux by challenging the competitive stature of existing products.

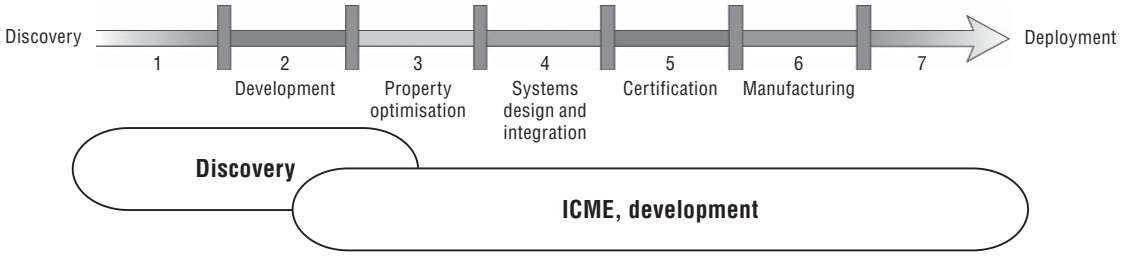
The 20th century was a golden age of invention and new technologies. Technology advancement in the 21st-century continues to accelerate. While scientists debate how long Moore's Law of scaling[2] will apply to increases in computing power based on silicon,[3] we have progressed well into the digital age that is characterised by global connectivity, on-command access to a vast array of digital information and resources, and the ability to store digital workflows that track all stages of engineering design and development, manufacturing, and commerce. Paradoxically, given the nature of global connectivity, these trends are more subtle, ubiquitous, and rapidly distributed than 20 years ago. Continued 21st century market punctuations are likely to arise at the intersection of big data and existing infrastructure and technologies, resulting in transformation of everyday means of communication, transport, and commerce. Creation and expansion of new products and even industry sectors can result. Accelerated materials discovery and development is about more than just anticipating, developing and addressing consumer demand and offering improved competitive products. New materials hold the promise to address many challenges highlighted by a US National Academy of Engineering study in 2009,[4] solutions to which are fundamentally limited by materials, such as the realisation of fusion energy, economical solar energy, carbon sequestration, managing the nitrogen cycle, access to clean water, restoration of urban infrastructure, and engineering the tools of scientific discovery. One can imagine an endless array of new modes of transportation and interpersonal communication. For example, adaptive materials can imbue environments with situational awareness and on-command flexibility via shape- and function-shifting multifunctional materials. Personalised mobile energy conversion and storage can allow people to work anywhere. One can envision that new and improved materials will enable replacements for diseased or damaged organs, sustainable food and water sources, non-toxic and recyclable replacements for consumer goods, molecular computing, and so on. The interfaces to these technologies will grow ever more subtle and less intrusive, as human-machine interfaces become more intuitive.

One of the earliest efforts aimed at designing and developing a material with targeted properties was initiated by the Steel Research Group (SRG) at Northwestern University in the 1980s (Olson, 1997; Apelian, 2004). The SRG built upon quantitative models for structure-property relations established in the physical metallurgy community to move away from "hit-or-miss" discovery of new and improved steels towards intentional design. Progress in computing power and computational materials science, physics and chemistry methods and tools over the ensuing decades has facilitated modelling and simulation of both the structure and properties of materials to inform decisions on how the material might be integrated into products. Properties such as thermal conductivity, strength, stiffness, toughness, and corrosion resistance can be intentionally designed into new structural materials, and at a a rapid pace, with assistance from materials theory and computation. Over the past decade, the integration of computational modelling and simulation with materials design and development has received considerable attention and focus through the Integrated Computational Materials Engineering (ICME) initiative in the United States (Pollock and Allison, 2008). The ICME approach aims at an increased pace of development of new and improved materials, more rapid integration of known materials into new products, development of new materials-based technologies, and the ability to improve existing products and processes. For example, the 2008 ICME study explains the initiative of the Ford Motor Company to develop cast aluminium engine blocks (Pollock and Allison, 2008). ICME has been strongly supported by industry, and serves to more closely integrate predictive computational materials science and engineering in materials design and development processes.

A foundational premise of the aforementioned US MGI is that the process of incorporating new and improved materials into products can be accelerated by promoting concurrency of the conventionally sequential and progressive phases of materials development and deployment shown in Figure 6.2 (adapted from Holdren [2014]). In other words, by anticipating downstream materials certification and manufacturing requirements during their initial development and laboratory-scale property optimisation, the time involved to deploy new and improved materials into products can be reduced from its historical average of 15 to 20 years down to perhaps 7 to 10 years or even faster. Moreover, costly and time-consuming iteration through steps 2 to 6 in Figure 6.2 can be reduced. Step 4 should consider specific manufacturing routes and product forms in the deployment phase.

The MGI contends that more seamless connectivity of experiments, computation, digital data and data science are needed both to speed up the pace of new materials discovery and to enhance concurrency of downstream steps. Materials discovery, traditionally serendipitous, is increasingly guided by combinatorial computational materials screening and can consider downstream integration and certification. In practical terms, the MGI is focused more on supporting materials discovery and early-stage development, while ICME is directed more towards accelerating the linkage from materials development through properties certification and product deployment. Increasingly, new materials are being developed for specific applications and products,[5] in contrast to the historical model of creating a range of available materials listed in a supply catalogue. This serves as a powerful driving force for the coupling of materials development into manufacturing, and requires incorporation of digital data in all phases.

Figure 6.2. **The historical sequential stages from materials discovery through deployment (from left to right)**



Source: Adapted from Holdren, J.P. (2014), "Materials genome initiative strategic plan", *https://mgi.nist.gov/sites/default/files/factsheet/mgi_strategic_plan_-_dec_2014.pdf*.

Important current trends in materials research and development enable the accelerated co-ordination of materials development and manufacture in the digital age:

- **The democratisation of quantum mechanics:** 30 years ago, computational quantum mechanics was the province of physics and chemistry, but it now pervades engineering education and practice as a toolset to support materials design and development, even in disciplines such as mechanical, aerospace, and civil engineering, as well as manufacturing sciences. Combined with computational materials science, multiscale micromechanics of materials, and ubiquitous computing, the utility of computation to support materials discovery and development is apparent.
- **Recognition of the hierarchy of material structure**, from atoms (sub-nanometre) to molecules to interfaces between multiple phase states of matter, and its important role in tailoring material properties for desired performance.
- **The ability to play "what if?" games** to explore potential performance of new and improved materials via predictive modelling and simulation.
- **Advances in high resolution materials characterisation and in situ measurements**, along with digital representation of these levels of hierarchy of material structure as part of the information to be coupled with digital manufacturing, along with traditional solid geometry model information and tolerances.
- **Manufacturing's embrace of information regarding materials science, chemistry and physics**, enabling consideration of complex effects of environment, manufacturing processes, and service conditions.
- **Digital recording of workflows regarding the history of how materials are synthesised or processed**, how their structure and properties are measured, and how they are used in specific manufactured products, the traceable "fingerprint" of a material pedigree. This combines with an information infrastructure (information theory, databases and data registries, digital interfaces and distributed e-collaboration).
- **Formal theory and methods to support decision making in materials development** (considering utility or value of information in supporting design decisions, goal programming, information economics, and methods for uncertainty management), integrated with digital workflows.

Perhaps the most potentially transformational trend lies in the intersection of big data and materials, which facilitates the pursuit of several of the other key trends in this list. For

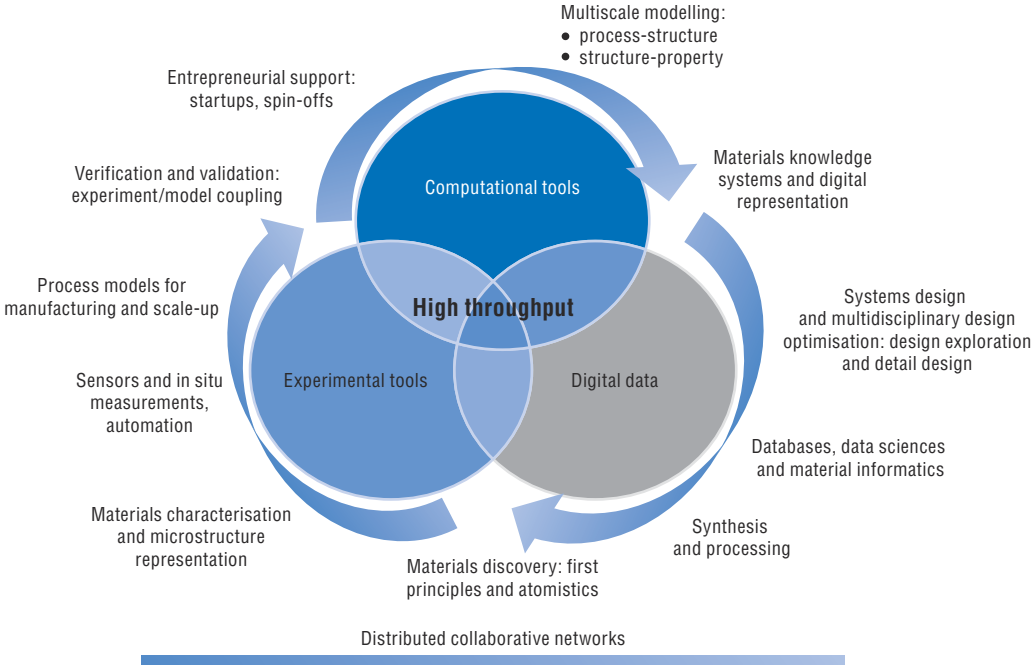
example, the big-data revolution pervades prediction of weather systems, climate change projections and cybersecurity (see Chapter 2). But the digital materials enterprise also stakes a claim in big-data "territory", albeit often understated, in particular with regard to the large variety and volume of materials data (Mellody, 2014). Computational modelling of the dynamics of behaviour of all atoms within even a cube of a crystalline metal that is a mere 1 millimetre on one side (about 15 times the thickness of a typical human hair) is a challenge comparable to other big-data applications. When materials are processed or placed in service, their structure often changes with time in ways that are also quite non-linear and dynamic. Such applications demand coarse-grained representations and models to be utilised to gain predictive understanding. The historical focus of the materials community on reduced order material descriptors such as measured "properties" has perhaps obscured this big-data character, although terabytes of information being generated from in situ experiments highly resolved in time and space are now becoming commonplace. The old paradigm of property catalogues may suffice for materials that have a long track record of service, but does not suffice for materials yet to be developed. Digital representation of material structure from the atomic scale upward conveys a wealth of information that offers value in downstream integration with manufacturing and deployment, and we have barely scratched the surface. For these reasons, it is necessary to take a broadened view of the materials development enterprise, as discussed next.

The materials innovation ecosystem

It is evident that the 21st century will act as a bridge from the dawn of the digital age into the era of ubiquitous computing, sensors and networking via big data – we stand on the threshold of the "Internet of Things". The convergence of advancements in data science and informatics, computational materials science, multiscale and multiphysics modelling, digital representations of material structure and associated metadata, in situ measurements and in-line process/manufacture diagnostics, automation and controls, uncertainty quantification and management, and integrated systems engineering offers the prospect to "close the loop" between materials development, manufacturing, and new and improved product development (McDowell, 2007). The notion of manufacturing ecosystems[6] has gained considerable traction,[7] as has discussion of industry ecosystems,[8] yet these notions have largely excluded emphasis on the primal and enabling role of materials discovery and development. This leads to the recognition of the need for a new kind of materials innovation ecosystem that can alter the relation of the materials supply chain to OEMs, and change the character of the modern research university and its relation to industry and government. Such an ecosystem can serve the needs of more intimate coupling of materials discovery and development with product manufacturing. A key to unleashing the power of such a materials innovation ecosystem is the ability to represent hierarchical material structure (including chemical composition) at multiple levels in digital format, along with data from results of simulations, experiments and various other sources of information and associated metadata (important additional information about the data), providing an objective basis for communication. These data are the "currency" of this ecosystem. As an example, the Institute for Materials[9] at the Georgia Institute of Technology (Georgia Tech) has fostered a vision for the materials innovation ecosystem shown in Figure 6.3 as a "test-bed" concept (McDowell and Kalidindi, 2016). The inner Venn diagram shows overlap of experiments, computation, and digital data, as per the MGI strategic plan (Holdren, 2014). It is at the core of a multidisciplinary, distributed, collaborative network that couples materials

development with manufacturing. To accelerate materials development, the methods should have a high-throughput character, requiring a digital information infrastructure for connectivity. This is a key point of departure from classical approaches to developing materials. Building on a well-established foundation of materials discovery, synthesis and processing, characterisation and microstructure representation, this ecosystem wraps together elements of materials data science and informatics; multidisciplinary systems design optimisation; materials knowledge systems; digital materials data and metadata; multiscale modelling; sensors and automation; unit process models for manufacturing; in situ measurements and manufacturing scale-up; and principles of uncertainty quantification, verification and validation, with entrepreneurship to form networks that can develop and make use of templated workflows to carry materials from the invention to application stages. Finally, an e-collaboration platform is essential for co-ordination of activities of the various experts and stakeholders involved in this digital infrastructure, shown in Figure 6.3. Basic research at universities can adopt a "use-inspired" (Stokes, 1997) paradigm that seeks to link downstream materials advances to key gap technologies, as well as disruptive new materials technologies such as nanostructured batteries for energy storage, ultra-strong materials, and materials for separations (Pearce, 2013).

Figure 6.3. **Elements of the materials innovation ecosystem, a cyber-physical infrastructure generalising the central theme of the US MGI focused on combining computation, experiment and digital data**



Source: Adapted from McDowell, D.L. and S.R. Kalidindi (2016), "The materials innovation ecosystem: A key enabler for the materials genome initiative".

New materials can be disruptive

In many cases, developing new materials can have more disruptive potential than improvement of existing materials. New materials can drive innovation. For example, fixation of implants via bone ingrowth into porous material structures replaced cement

fixation and revolutionised hip replacement technology decades ago.[10] According to information from the European Commission,[11] "70% of product innovation is estimated to be based on materials with new or improved properties."

Advances in vulcanised rubber[12] in the 19th century constitute an important historical example of a modification of a natural or synthetic rubber to achieve enhanced durability via the addition of sulphur or other additives that affect cross-linking of polymer chains. An extensive range of transformative polymer-based products have been developed, bringing about significant advances in automotive tyres, orthopaedic materials, composite materials, and many other applications. One goal of modern materials discovery and development in the next product revolution is to replace the trial and error discovery approach by a more systematic, computation-assisted strategy. As illustrated in Figure 6.2, discovery precedes materials development.

More systematic, scientific approaches to materials discovery are evidenced in two examples. The mission of the Materials Project[13] is "to accelerate the discovery of new technological materials through advanced scientific computing and innovative design." Important aspects of this effort include software, novel supercomputing strategies, and screening methods to assess new materials for specific applications. By pursuing scalable computational materials science over supercomputing clusters, the Materials Project has predicted several new battery materials which were made and tested in the laboratory. It has also identified new transparent conducting oxides and thermoelectric materials using this approach. QuesTek Innovations LLC[14] have combined ICME methodologies with their Materials by Design technology to rapidly develop new high-performance alloys, coatings and other materials. This is accomplished by coupling physics-based, cyber-enabled expertise and design tools with advanced characterisation techniques to minimise costly and time-consuming experimentation in order to rapidly focus on a few iterative prototypes that are scaled up. Examples of designed materials include commercially available Ferrium steels, as well as alloys under development based on aluminium, titanium, nickel, molybdenum, tungsten, niobium, copper, cobalt, and other materials. Their Fe-based Ferrium steels are being evaluated and used in a wide range of demanding and safety critical applications in aerospace and e.g. the oil and gas industries.

The importance of improved materials

A simulation-assisted approach to materials development can reduce time and cost as companies eliminate repetitive tasks with fewer iterations. ICME strategies that employ materials simulation to inform materials development decisions can facilitate better products, such as stronger and more highly complex hierarchical structures. Successful integration of materials modelling and data science into decision support for product development can also shorten the time between materials discovery and their commercial use. In the past, this period could stretch to 20 years or more (Holdren, 2014). The Accelerated Insertion of Materials (AIM) programme, run by the US Defense Advanced Research Projects Agency (DARPA) from 2000 to 2003 (McDowell and Olson, 2008; McDowell and Backman, 2010), had considerable impact as a case study by developing and integrating a suite of process and microstructure-property models along with uncertainty analysis to optimised forged nickel-base superalloy gas turbine engine discs. AIM demonstrated significant time savings. For example, in aerospace engine design, concurrent optimisation of design and manufacturing processes allowed the design of a rotor disc that was 21% lighter and 19% stronger than other models in half the time of a typical development cycle (Holdren, 2014).

This has the potential to transform the materials supply chain. Large companies will increasingly compete in the development of materials. This is because "if you have a proprietary manufacturing process which applies to proprietary materials, you are creating a long-lasting competitive differentiation" (The Economist, 2015). In other words, materials innovation within OEMs and their supply chains will provide the benefit of staying ahead of the competition in new product development. The resulting knowledge management systems are not only algorithmic in nature but also involve an embedded culture and cannot be easily reproduced. Furthermore, companies can identify future disruptive technologies while improving existing materials within their innovation ecosystems.

The digital materials and manufacturing thread

Digital manufacturing is defined as the use of an integrated, cyber-enabled system comprised of three-dimensional (3D) visualisation, simulations, analytics, and various collaboration tools to simultaneously create product and manufacturing process definitions.[15] An August 2015 McKinsey and Company article[16] states that "Industry and academic leaders agree that digital manufacturing technologies will transform every link in the manufacturing value chain, from research and development, supply chain and factory operations to marketing, sales, and service." The report goes on to say that manufacturing generates more data than any other industry sector, yet much of it is not harnessed. It states that "digital transformation of the $10-trillion-plus global manufacturing sector will play out over a decade or more," and that "Boeing developed its two most recent airframes, for the 777 and 787, using all-virtual design, reducing time to market by more than 50 percent." Airbus is actively pursuing development and implementation of composites and other advanced materials in aircraft design and manufacturing, developing technologies to improve the rate of composite manufacturing.[17] This runs entirely parallel with the materials development enterprise, which is most often viewed as part of the manufacturing supply chain, somewhat divorced from the datasets considered in digital manufacturing. The concept of a "digital twin"[18] has been introduced in reference to a virtual digital representation of a physical system, such as a 3D model of an object or collection of parts in sub-assemblies or assemblies, which can potentially be used to represent the form and function of physical objects in digital computing. The digital twin concept includes the possibility of using sensor feedback from the actual system as a means of monitoring and controlling the response of the virtual representation. Similar to the concept of augmented reality in video games, it is envisioned that the digital twin will faithfully represent all appropriate physics associated with the system response, complex interactions, and even degradation or failure. In other words, the digital twin can serve as a means to create, build, and test equipment and manufactured parts in a virtual environment.[19]

To deal with the deluge of information from sensors that will be gathered in future NASA and US Air Force vehicles under extreme service conditions, Glaessgen and Stargel (2012) have argued that traditional fleet management approaches are too limited, and uncertainty associated with limited data is too high given the time lags and limited data content involved in typical physical inspection schemes. The concept of a digital twin that links with the vehicle's on-board integrated vehicle health management system, maintenance history, and available fleet data, including historical data, to mirror the remaining lifetime expectation of the actual physical flying twin is envisioned as the basis for desirable future platforms. This digital twin concept has even been proposed for use in assessing the health and maintaining a fleet of military aircraft.[20]

To provide a realistic surrogate for the actual system, the digital twin concept must also material structure and behaviour. It is also clear that the uncertainty of models of material behaviour and in-service degradation of materials, either based on simulation or data correlations, should be incorporated within the digital twin concept. In the spirit of anticipating downstream certification for applications shown in Figure 6.2, materials can be designed or redesigned based on digital twin response and comparison with behaviour of fielded systems. This leads to the prospect of continuous improvement in fleet quality, e.g. by coupling new and improved materials development with critical fleet components. ICME (Pollock and Allison, 2008) involves the incorporation of computational methods and data science to inform decisions made in materials development for product applications. Digital representation of random microstructure and predictive computational structure-property relations over a range of realistic microstructures are key enabling technology components of ICME. This necessitates integration with manufacturing processes, including digital CAD files with both geometric and materials information related to manufactured components, along with supporting information regarding inspection, process control and quality control.

Additive manufactured parts for tooling, repair and replacement parts, and prototyping are excellent candidates for the digital twin concept. Additive manufacturing has the potential to create new material forms to enable new and improved products, and facilitates the realisation of location-specific properties that vary throughout the part in a manner that in some way optimises performance for a given set of system requirements (see Chapter 5).

Challenges for the future of accelerated materials innovation

As outlined in the introduction to this chapter, significant challenges must be address to realise the promise of cyber-enabled accelerated materials development and manufacturing. These are discussed in the remainder of this chapter, with major policy issues enumerated in the conclusions.

Building the culture of the materials innovation ecosystem

Economies that stand to benefit most from this emerging vision of the integration of cyber-enabled materials development and product manufacture are those that can most effectively develop and sustain the necessary culture of innovation. Key ingredients include a more robust materials supply chain, distributed service providers, and digital data and workflow tracking. This culture change will probably be led by universities via future workforce development and OEMs through embracing materials innovation in applications, leveraging government investment and influencing policy making.

The materials innovation ecosystem in Figure 6.3 is a human-centred, cyber-physical infrastructure aimed at providing decision support to processes of materials discovery and development. It does not replace best practices but embeds them. The necessary culture for this ecosystem to flourish emphasises distributed, collaborative stakeholders and experts in all phases shown on the periphery in Figure 6.3. The ecosystem is too extensive to be built around a single discipline such as materials or manufacturing. Universities will struggle with its scope, which tends to defy characterisation within individual academic units or even colleges. Small to medium-sized companies may wonder how to prioritise investments with limited resources or how to focus their own resources to collaborate with others. Large companies and industry sectors may wish to develop their own internal ecosystems as a subset approaching the scale and scope of the vision in Figure 6.3.

The digital data aspect is key not only to material structure representation and integration of materials and manufacturing, but also for tracking collaborations and communications for a given materials discovery and development effort – in other words, templated workflows of digital information and decisions. The entire process is quite amenable to modern data science. Pursuit of the materials innovation ecosystem will open many new opportunities for specialised service providers who can provide data, data science, materials synthesis and processing, materials characterisation and property testing, uncertainty quantification, modelling and simulation, and various other decision support tools on an as-needed basis. This can result in a recasting of the role of materials and manufacturing supply chains. It must be systemically and organically developed and sustained through education, training, and identification of best practices. Moreover, moving to an ecosystem for materials innovation enabled by a digital information infrastructure requires building on the emergent communities in data and data science, so that career categories such as "materials data scientist" will become commonplace. Along with high-throughput methods, there should be as much emphasis on a culture of connectivity between distributed experts in the ecosystem as on specific technologies. In this ecosystem, quantifying and managing uncertainty in data and models is essential to support decision making in materials development and investments in scale-up of manufacturing.

In addition to improvements in linking new and improved materials to enhanced product development and manufacture, there are other important capabilities that accrue to this technology, including but not limited to:

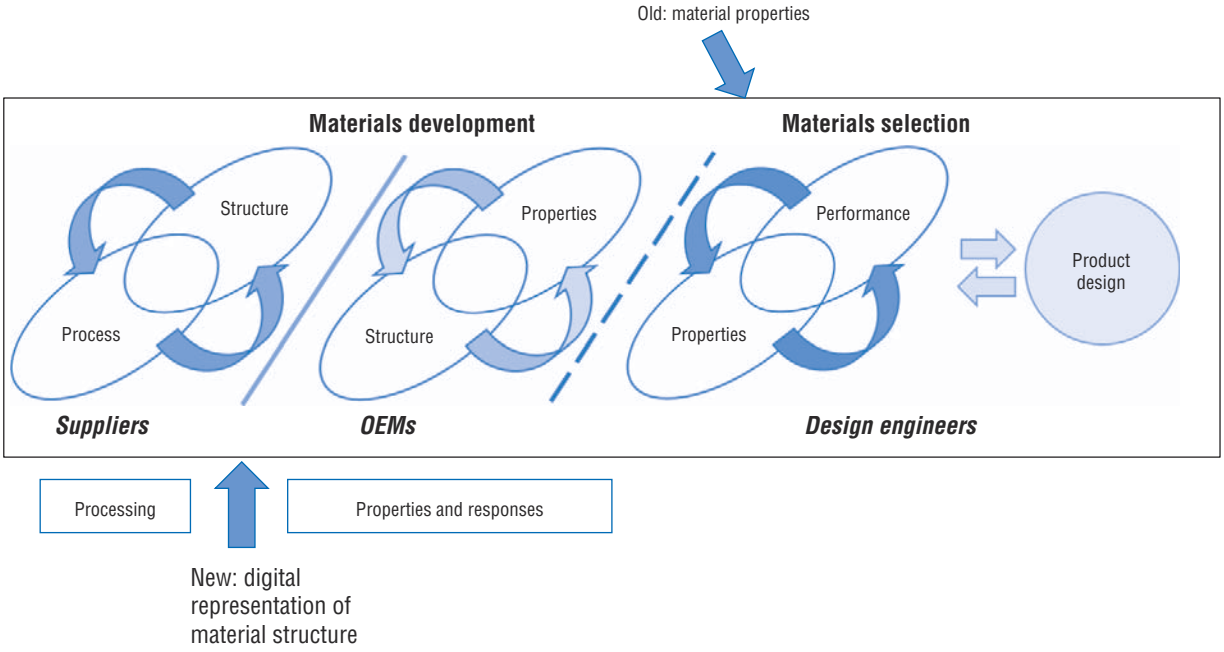
- Prioritising research and development initiatives in government agencies.
- Prioritising the blend of experiments and computational models in terms of their utility in supporting decisions in new and improved materials development, considering return on investment. Empirical routes to materials development that rely on time-consuming experimental protocols are costly. The question is how these protocols can be reduced by reliably supporting decisions in materials development based on information from modelling and simulation, as well as advanced data correlations.
- Prioritising mechanisms and materials science phenomena to be modelled for a given materials design and development problem.
- Conducting feasibility studies to establish probable return on investment of candidate new material systems.

Integrating a cyber-enabled materials supply chain

Figure 6.4 shows how a future emphasis on digital representation of material structure as a means to communicate with design and product development will change the role of the materials supply chain relative to historical practice shown in the lower right inset in Figure 6.1. With the focus shifted to emphasise digital representation of the hierarchical structure of materials (solid slanted line to the left in Figure 6.4), instead of the historical focus on properties (dashed slanted line to the right), materials suppliers are required to maintain and convey digital structure information. This disrupts and evolves the traditional supply chain-OEM-manufacture relationship based on meeting nominal structure metrics and property specifications from the OEM. In particular, digital information regarding the structure of materials, along with related structure-property information, will be the medium of communication to virtual design and manufacturing tools used by OEMs and other customers. This includes metadata regarding property

measurements, models based on simulation and/or data analytics, and details of all the steps in the material's process history, i.e. how the material is made. This will also shift much of computational materials engineering onto the supply chain, with new demands to be met by digital materials service providers. Customisation of materials to address product-specific performance requirements can be addressed on a contractual basis within such an ecosystem (it is difficult at present), and small to medium-sized new companies specialising in customisation will populate the interface between materials supply and OEMs. A good example is QuesTek LLC, mentioned earlier. Data science companies can provide data services and analytics to assist in identifying potential new materials or improvements in coupling materials to manufacture. Public-private consortia and investment in future workforce development will be necessary to build the culture of this new paradigm.

Figure 6.4. **Shift from historical focus on materials selection to digital representation of the material's structure to support materials development**



Source: Adapted from McDowell, D.L. (2012), "Materials genome initiative: Implcations for university education and research", *www.brown.edu/conference/mgi-town-meeting/sites/brown.edu.conference.mgi-town-meeting/files/uploads/McDowell_presentation%20%5bRead-Only%5d%20%5bCompatibility%20Mode%5d.pdf*.

E-collaboration and web agent approaches to distributed materials and manufacturing

The materials innovation ecosystem shown in Figure 6.3, coupled with the manufacturing ecosystem within a given industry sector, is inherently distributed. Competition within the supply chain of the ecosystem for both materials and services (e.g. data, data science, experiments and computation) can serve to both accelerate processes and reduce cost.

Given the central role of digital information in materials innovation, the sharing of digital data is a key issue. Incentives are key to motivating the mutually beneficial sharing of information (McDowell, 2013). New journals such as *Integrating Materials and*

Manufacturing Innovation[21] will continue to be spawned that are expressly devoted to innovation at the interface of digital materials and manufacturing, as more established journals seek to identify their niches in this new digital materials era. In the United States, the National Institute of Standards and Technology (NIST)[22] is at the forefront of materials data registry and open data initiatives for the MGI. Related data archival activities are distributed across multiple government agencies involved in the Subcommittee of the MGI (SMGI).[23]

Clearly, it is difficult to comprehend how a single company could mount such a highly distributed arrangement that combines pre-competitive information and best-in-class service provider capabilities with proprietary datasets and applications. In the long-term, materials and manufacturing stakeholders will be globally distributed, and will assemble various elements of a cyber-physical infrastructure to support materials innovation. Still in its early stages, underdeveloped technology components of this infrastructure currently include i) high-throughput materials synthesis/processing, characterisation and property measurement; and ii) information infrastructure (McDowell et al., 2014). Distributed platforms and service providers can offer elements of materials information infrastructure that support many of the aforementioned goals. Such platforms and service providers could afford services ranging from modelling materials via quantum mechanics through finite element methods, high-throughput methods for discovery and development and modern data sciences applications. Relevant examples of platforms and service providers include, but are not limited to, the aforementioned Materials Project at the Lawrence Berkeley National Laboratory (LBNL), the Open Knowledgebase of Interatomic Models (OpenKIM) project on interatomic potentials at the University of Minnesota,[24] the NIST Center for Hierarchical Materials Design (CHiMaD)[25] at Northwestern University, Argonne National Laboratory and the University of Chicago, and the US DOE PRISMS Center at the University of Michigan.[26] Materials data registries and model repositories include those at NIST,[27] Citrine Informatics,[28] NanoHuB,[29] and the National Data Service's Materials Data Facility.[30] Similar nodes exist in Europe (e.g. the Novel Materials Discovery [NoMaD] computational materials repository[31]) and Asia (e.g. National Institute for Materials Science [NIMS] in Japan[32]). By and large, these platforms do not address distributed e-collaboration.

There are certain potential manifestations of the envisaged materials information infrastructure that have not previously existed and which create new market niches, most of which could be integrated within the e-collaborative framework. These include:

- digital material data registries and repositories
- web- and cloud-based data services and applications that add value by aiding interpretation of data to support materials discovery and development
- web agents and service vendors for modelling and simulation support tasks
- assignment and certification of the "readiness level" of data as well as modelling and simulation tools
- services vendors that couple materials to unit manufacturing processes (for example, computational models or advanced correlations for machining or processing of metallic articles).

This information infrastructure can be broadly distributed and leveraged, with extensive "plug and play" attributes.

Future workforce development

Examples of already existing academic course offerings and programmes that address materials innovation include the master's programme in Materials Science and Simulation at the Ruhr University Bochum,[33] ICME courses at Mississippi State University,[34] Northwestern University's ICME Masters certificate focused on design,[35] and the Georgia Tech From Learning, Analytics, and Materials to Entrepreneurship and Leadership (FLAMEL) programme (NSF IGERT).[36] Summer programmes include the Texas A&M IIMEC Summer School on Computational Materials Science Across Scales,[37] the University of Michigan Summer School on Integrated Computational Materials Education,[38] the Lawrence Livermore National Laboratory (LLNL) Computational Chemistry and Materials Science Summer Institute,[39] and the summer workshop from University of Florida Cyber-infrastructure for the Atomistic Materials Science Center.[40]

Box 6.1. **Imperatives for the future workforce**

The new materials innovation ecosystem will require major shifts and broadening of the skill sets of the materials development workforce. University curricula and instructional tools should be refined and extended to integrate various elements of the materials innovation infrastructure shown in Figure 6.3. This reformation must extend beyond traditional materials education to bridge across engineering and science academic disciplines that naturally foster various supporting elements. For example, there is a significant gap in curricula at universities in addressing uncertainty quantification and protocols for decision support in materials development. This gap has emerged from a focus in the materials community on the bottom-up scientific method to discover and develop materials, largely removed from consideration of product level systems engineering. Treatment of uncertainty generally falls under the categories of systems design, data sciences, and optimisation under uncertainty.

There is a need to develop and offer cross-cutting curricula and short courses in engineering and the sciences that address computational materials science, high-throughput experimental methods, advanced materials characterisation and property measurements, inverse methods and metamodelling, uncertainty quantification, verification and validation, data science, and systems integration with manufacturing. Quantifying uncertainty in materials process-structure and structure-property relations has a rich scientific depth, in addition to its economic imperatives. Addressing uncertainty quantification and its management in concert with systems engineering can dramatically accelerate materials innovation efforts, as outlined in a recent study[41] of The Minerals, Metals and Materials Society (TMS). As a service to future workforce development, Georgia Tech's Institute for Materials has produced on Coursera[42] two massive open online courses (MOOCs) supportive of the MGI. The two courses are Materials Data Sciences and Informatics[43] and Introduction to High-Throughput Materials Development.[44]

Data challenges offer incentives to develop mechanisms to gather all necessary elements of data science, experiment, and computation and draw the attention of the future workforce to accelerated materials discovery and development. A good example is the recent Materials Science and Engineering Data Challenge sponsored from 2015 to 2016 by the US Air Force Research Laboratory in partnership with NIST and the US National Science Foundation.[45]

Road mapping and capitalisation of the materials innovation infrastructure

The US MGI has clarified the core elements of the materials innovation infrastructure as comprising the intersection of experiments, computational modelling and simulation, and data (e.g. registry, storage, analytics). This is shown at the centre of the materials innovation ecosystem depicted in Figure 6.3. However, investment in materials research infrastructure to date in most developed countries has focused on high-end materials synthesis and characterisation facilities, with less attention devoted to high-throughput methods to process and characterise materials. Materials data science and informatics is in early, formative stages. Few universities in North America, Europe or Asia have well-developed curricula in this regard. Beyond digital information, the materials innovation infrastructure also requires physical infrastructure for: i) high-throughput materials synthesis and processing, ii) characterisation, iii) property measurement; and iv) high-performance computing and data storage.

Fortune 500 companies such as IBM[46] and small and medium-sized firms such as Wildcat Discovery Technologies, Inc.[47] have made initial investments in order to mount an integrated materials innovation infrastructure that couples experiment and computation with data science for materials discovery. Investment in related infrastructure necessary to produce manufactured goods in a variety of sectors – from transportation, to energy and security – has been slow. This is particularly true with regard to shared user facilities. Indeed there is a question of how to invest in new cross-cutting shared user facilities necessary for accelerated materials discovery and development, such as high-throughput instrumentation for materials characterisation, property measurements and materials synthesis and processing. In a manner analogous to high-end scientific infrastructure for materials research such as synchrotron x-ray and neutron diffraction, these facilities should be distributed in nature, i.e. regional, national, and even international. Corporate investment is likely to be sector- and even material system-specific. Private sector investment may not facilitate a broader development of the materials innovation infrastructure that serves the common needs of pre-competitive screening and scaled-up evaluation for materials solutions.

In many respects, the materials innovation ecosystem underlying the aspirations of MGI and ICME has analogies to the inter-agency National Nanotechnology Initiative (NNI)[48] begun in the late 1990s, an initiative that fostered distributed nanotechnology research throughout the United States. The MGI has been similarly framed in terms of fostering a distributed materials innovation infrastructure that aims to accelerate the pace of discovery, development and deployment of new and improved materials into products, with the objective of reducing the time and cost involved. But a key distinction between the infrastructure of the materials innovation ecosystem and the infrastructure initiative of the NNI is an emphasis in the former on high-throughput tools and strategies. In addition, the MGI focuses on "closing the loop" between experiments, computational modelling and simulation, and data sciences and informatics to promote concurrency of early-stage research and development (R&D) with considerations of certification, manufacturability, and long-term service requirements for materials systems. In the United States, much of this infrastructure already exists or is under active development, but lacks organised connectivity across materials classes, with limited support for access. Furthermore, there are no clear mechanisms to identify gaps and prioritise elements for inter-agency funding that cut across the broad materials innovation ecosystem. Efforts to date are most often localised in specific academic institutions, government research laboratories, and industries. There is limited awareness among the broader community of distributed capabilities or of how to combine them across the elements of the materials innovation infrastructure.

Important insights and perspectives can be drawn from the report of the workshop Building an Integrated MGI Accelerator Network, held at Georgia Tech, 5 to 6 June, 2014 (McDowell et al., 2014). This workshop assembled 150 thought leaders and stakeholders from academia, industry and government in the United States to explore how distributed experimental, computational, and materials information infrastructure might be further developed and collaboratively networked to most efficiently realise the vision of the MGI. Co-organised by Georgia Tech, the University of Wisconsin-Madison, and the University of Michigan under the auspices of the Materials Accelerator Network,[49] the event initiated a national dialogue regarding community MGI priorities and the path forward. A set of opening plenary talks outlined the government MGI strategy and shared industry and academic perspectives on accelerating materials discovery, development and deployment. Plenary talks were followed by breakout sessions organised to cover a broad range of application domains, including materials for organic and inorganic electronics, structural materials, materials for energy storage and conversion, biomaterials and bio-enabled materials, and materials and interfaces for catalysis and separations. Breakout sessions explored and discussed three specific themes: critical issues and technology gaps, infrastructure for MGI integration, and a strategy for road mapping a materials accelerator network.

Box 6.2. **Critical issues and technology gaps in accelerating materials discovery and development**

Summarising from the report of the workshop Building an Integrated MGI Accelerator Network (McDowell et al., 2014), some of the critical issues and technology gaps that must be closed to realise the vision of MGI cut across these application domains:

- **Materials information infrastructure**, particularly web-based environments for e-collaboration and data sciences.
- **High-throughput strategies for screening and development** that consider capabilities and constraints on available synthesis and processing routes, including fast acting modelling tools to assess the probability of meeting requirements.
- **Future workforce development**, with an integrated perspective on coupling of experiments, computation, and data sciences.
- **Fundamental understanding** of the **relations between structure at different length scales and materials properties/performance.**
- **Advanced diagnostic methods**, particularly in situ/in operando.
- **Consideration**, at early stages of discovery and development, of the **long-term stability of materials** under service conditions, environmental stability, degradation and performance lifetime.
- **Predictive simulation of metastable states and non-equilibrium trajectories** of evolution under service conditions for applications, enabling parametric exploration of candidate materials for product applications. Metastability of a material refers to its useful operation away from the system's state of least energy. Many useful engineering materials are metastable.
- **Measurement science and modelling and simulation of synthesis and processing.**
- **Principles of kinetic and thermodynamic control of process route/structure relations.** The challenge is knowing how to exert reliable control of structure over various length scales (nano-macro) during processing, including up to large scales.

New kinds of data science strategies and distributed user facilities are necessary to address the gaps identified in Box 6.2, in addition to education and training. High-priority recommendations to close key gaps identified in this workshop (McDowell et al., 2014) included the following:

- Focus on education and training of the future MGI workforce.
- Compile a knowledge base of existing MGI-related efforts in the United States.
- Link physical- and cyber-infrastructure that cut across materials classes and application domains.
- Establish working groups and networks in and across these materials domains.
- Define common foundational engineering problems for each materials application domain to rally MGI stakeholder collaboration and networking.
- Establish a stronger materials innovation infrastructure.

Conclusions

With the confluence of advances in predictive computational materials modelling, data science, and high-throughput methods for materials screening, significant opportunities exist to substantially decrease the time to bring new and improved materials to market in next-generation products. Emerging technologies such as on-demand 3D printed parts hint at the demand for mass customisation and rapid deployment of new materials. The rates of discovery and development of materials to enhance downstream product competitiveness can be accelerated significantly by coupling historically empirical, experimentally based strategies with computational simulation and data science strategies. Furthermore, new kinds of high-throughput shared user facilities are essential to rapidly make materials, measure their structures and properties, and screen for applications to refine for manufacturing scale-up. Unprecedented recent advances in combinatorial search methods for new materials can further interplay with accelerated materials development to revolutionise new product designs and performance.

The analysis of incentives for materials development in response to many 21st-century grand challenges largely revolves around economic viability, sustainability and evidence of societal impact. The design of the necessary incentives requires appropriate government strategies and policies. Moreover, the promise of "democratisation" of customised products offered by ubiquitous technologies such as 3D printing and incorporation of sensors and communications within materials to facilitate the Internet of Things (Burrus, 2014) has global implications, analogous to the profound influences of cellular smart phone technology and social media.

Given the strong competitive product edge that each new and improved material can confer for a limited period of time, it stands to reason that data and intellectual property (IP) challenges are critical issues. For major product innovation with new and improved materials, there is only a limited window of time after product release during which to gain market share. This window continues to shrink as the time to introduce new highly competitive materials is compressed. There are multiple IP-related questions. For example, who owns the data? Who owns the infrastructure? Who owns value-added information or capabilities? How are open development contracts differentiated from proprietary contracts? Materials are often core to new and improved product capabilities – will the existing international patent system be sufficient to protect competitive advantage? Suppliers can

potentially control more IP in a state-of-the-art materials innovation ecosystem because they will be responsible for curation of the digital workflow documenting materials development. What is the background IP and how is it defined? How much pre-competitive collaboration is desirable to compete in the space of new products? Can development costs be shared? What are best practices models for pre-competitive development of shared technologies and cyber-physical infrastructure? How can companies differentiate based on downstream development and applications? There are no easy answers to these questions, but a competitive marketplace will inexorably drive the distributed materials innovation infrastructure forward in an increasingly connected digital world. It is clear that no single company or organisation will be able to "own" the array of technologies associated with an e-collaborative materials innovation ecosystem. Nor is this desirable, since the interconnected global economy can benefit broadly by contributing goods and services to the ecosystem. OEMs can focus on utilising this ecosystem to maximise benefit in new product development and reduce time to market, with the caveat that competitive advantage will focus more on increasing the pace of introducing new products and not relying solely on their intrinsic value, absent disruptive advances in new product capabilities and/or creation of new markets. Hence, a public-private investment model is warranted, particularly with regard to building the cyber-physical infrastructure and in future workforce development.

Appropriate, enlightened regulatory policies could help to foster this ecosystem, emphasising the need for maintaining a largely open and accessible cyber-physical infrastructure and still providing safeguards for product-specific information and workflows. There are currently major efforts to develop the early materials information infrastructure and associated data standards in professional societies[50, 51] (Robinson and McMahon, 2016). There is also a need for policy co-ordination across the materials innovation infrastructure at national and international levels. The need for 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. This is a good example of where existing structures and regulatory policies may not suffice, as they were developed for a different era.

Cyber-enabled design and development of materials also raise entirely new policy issues. Some issues are of strategic character, even having security and stability implications. For example, the motivation for replacement of rare earths in magnets and electronic materials involves consideration of the stability of materials supply and associated geo-politics. Such considerations can drive the search for new materials. Moreover, new cybersecurity risks can be anticipated since a digital, computationally assisted materials "pipeline" relying on various forms of data could be hacked or otherwise manipulated. Well-conceived and designed policies are needed for open data and open science (e.g. for sharing simulations of materials structures, or for sharing experimental data in return for access to modelling tools) (McDowell, 2013). Principles for negotiation of IP rights in the new materials innovation ecosystem among distributed stakeholders are a pressing short to medium-term issue, as new kinds of agreements will probably be necessary to distinguish open-source, shared data design environments from design and development scenarios with closed and proprietary character. Progress on new materials requires close collaboration between industry, universities, research funding agencies and

government laboratories. Steps are also needed to foster interdisciplinary research and education, because materials research is inherently multidisciplinary (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 addition to changes in university curricula, as well as a shift from traditional modes of interaction of materials suppliers and OEMs in industry, proprietary information and licensing issues, etc., there are a number of potential technology barriers to further development and use of these kinds of methodologies. Often, models are either non-existent or insufficiently developed to support decisions to select among various potential designs or development routes. This includes models for both process-structure relations and microstructure-property relations. A particular need is the co-ordination of model repositories for rapid availability to support design optimisation searches. A complicating factor that is rarely addressed is the quantification of uncertainty of model parameters and model structure as necessary to support robust design of materials (McDowell et al., 2010). Uncertainty quantification of models is best performed during model construction and calibration or fitting of parameters by model developers, rather than by downstream users. It is incumbent upon funding agencies and review processes to require uncertainty quantification (UQ) of models and data as part of R&D proposals. This will require much more emphasis on UQ in the materials community, including new courses and emphasis on UQ in related university curricula. There is a pressing need for methods and policies governing access to distributed service providers, or "web agents", for models (McDowell et al., 2010), along with definition of "readiness levels" for these services addressing provenance, degree of validation, and support for usage and sustainment, analogous to well-known technology readiness levels (TRLs) in the US Department of Defense (US DoD).[52]

Deliberation between research bodies, firms, government research laboratories, standards organisations, and professional societies working on development of new and improved materials have predominantly been concerned with the compatibility of data formats. But this needs to evolve towards a focus more on how to use these data to support decisions in materials discovery and development, along with considering many of the foregoing policy issues. Data formats and protocols vary widely and digital platforms and data structures change rapidly. Access to and dedication of high-performance computing and cloud storage resources is an important element to which pre-competitive public-private consortia and government policy can contribute. Initiatives such as ICME in the United States and the Integrated Computational Materials Engineering expert group (ICMEg)[53] in Europe are all wrestling with these issues to some extent. In addition, cyber-physical infrastructure relating to high-throughput methods for rapidly making new materials and assessing stability, performance and suitability for products is of high value to a range of stakeholders; there is a need for broad community access to user facilities.

As discussed in this chapter, large-scale initiatives are under way in North America (MGI, ICME), Europe (ICMEg, Horizon 2020)[54] and Asia to systematically build the science base and infrastructure to support more rapid materials innovation and linkages to manufacturing (methods and tools, materials data infrastructure, shared facilities, and future workforce development). Progress is inexorable but its rate is currently limited by lack of co-ordinated planning and investment. Policies and regulations must be updated to reflect the modern era of materials development in which high value is placed on digital data and its co-ordinated, collaborative exploitation to support materials design and

development decisions. Policy making at national and international levels can strongly influence the rate of development of the materials innovation ecosystem, broaden the potential pool of collaborators, and promote adoption of more efficient investment strategies. Some of the key policy requirements may be summarised:

- Allocate R&D investment in pre-competitive materials data registries, high-performance computing, and high-throughput experimental infrastructure. This investment is necessary to cultivate and support the culture of the materials innovation ecosystem.
- Empower the materials supply chain through policies that promote digital representation of material structure as specifications beyond an exclusive focus on property sets.
- Promote and reward efficiency of distributed e-collaborations of industry, government, and academic stakeholders involved in materials development.
- Encourage accessible digital data as a product of publicly funded research.
- Develop strong incentives for researchers and developers to share materials data by adding value to the curation, analysis, and management of the data provided, including access to state-of-the-art advanced correlations and UQ methods.
- Address the IP barriers to sharing data and data analytics that may affect specific product development or competitive advantage to industry by fostering development of an extensive pre-competitive common infrastructure that can accelerate materials insertion.
- Establish incentives for universities to adopt cross-cutting curricula and other educational or training platforms that support and nurture the materials innovation ecosystem across e.g. engineering, the sciences, computing and management.
- Road map the development of the materials innovation infrastructure and prioritise investments at regional, national, and international levels.
- Foster formation and development of distributed small to medium-sized companies with specialisations ranging from materials data services, high-throughput screening, materials computation and design, to materials suppliers that can provide services upon demand to support accelerated discovery and development of materials for manufacturing.
- Develop regulations and certification protocols governing engagement of distributed web- or cloud-based service providers in materials discovery, development, and scale-up manufacturing.
- Emphasise the need for sustainable materials and product solutions.

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PART II

Cross-cutting themes

The Next Production Revolution
Implications for Governments and Business
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PART II

Chapter 7

The next production revolution and institutions for technology diffusion

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Institutions for technology diffusion facilitate the spread and use of new knowledge and methods that can assist companies in adopting new manufacturing technologies. Such institutions also help companies to achieve objectives ranging from improved production efficiency to product development, strategic planning, and training. This chapter examines publicly oriented technology diffusion institutions and their rationale, organisation, and services. Case studies of varied approaches are presented, including dedicated field services, technology-oriented business services, applied technology centres, information exchange, and demand-side incentives, and effective practices and operational insights are distilled. Key policy suggestions include the need for greater recognition that strong institutions for technology diffusion, in conjunction with complementary framework measures, are essential for widespread deployment of the next production revolution. Technology diffusion institutions should be encouraged to share and refine their practices, build collaborative partnerships, and address missions of sustainability and responsibility. Particular attention is required to assist small and medium-sized enterprises (SMEs) and to address governmental failures in technology diffusion.

Introduction

Institutions for technology diffusion will be vital in spreading the use of next-generation production technologies. If institutions and mechanisms for technology diffusion are weak, and firms and industrial systems lag in absorbing and effectively using the new technologies and approaches, then the next production revolution could stall. But these institutions also need to change and innovate to achieve diffusion effectively and responsibly. This chapter examines the nature and role of institutions for technology diffusion. It also explores how these institutions are changing, and may need to change, to respond to and influence the development of next-generation production technologies.

Over the coming decade, major transformations are anticipated in how the world makes and uses manufactured goods and services (Kagermann, Wahlster and Helbig, 2013; Foresight, 2013; Buffington, 2016). The technological drivers of this "next production revolution" include burgeoning developments in information and communications (such as big data, cloud computing, and the Internet of Things [IoT]), the rise of digital and additive (3D) manufacturing, and the emergence of new bio- and nanomaterials that offer novel functionalities (OECD, 2016). Parallel changes are expected in manufacturing business models, with greater openness, flexibility, customisation, user engagement, interaction, and attention to value-added services and sustainability, as well as adjustment in how manufacturing firms are organised, who they employ, and where they are located (OECD, 2010a; Chesbrough, Vanhaverbeke and West, 2014; Wu et al., 2015; Prendeville et al., 2016). For advanced economies, there is the hope that the next production revolution can revitalise older industrial regions and strengthen national industrial competitiveness through "smart" factories with the agility, efficiency, and intelligence to raise productivity and obviate the need for offshoring (Alessi and Gummer, 2014; Brennan et al., 2015; NAE 2015; The White House, 2016). For emerging economies, advances in manufacturing technologies and methods offer fresh opportunities to engage in higher-value and more sustainable production (Birtchnell and Hoyle, 2014; Rauch, Dallasega and Matt, 2016).

In past decades, predictions of major technological transformations in industry have not always been realised (Youtie et al., 2007), as with expectations of automated factories in the 1950s or the spread of molecular machines in the 1980s. Bottlenecks that constrain, or at least slow down, radical technological ideas can include economic viability, financing, market demand, strategic fit, technical readiness and time-to-implementation, the power of incumbent technologies and the appearance of unexpected alternatives. The latest expectations about technological transformation in manufacturing certainly face such issues. Additionally, in the coming period, the promise of the next production revolution could be moderated, if not stymied, if it fails to address a series of fundamental societal and institutional challenges. A number of these challenges are already evident, such as concerns regarding human workers being replaced by robots, fears about autonomous machine decision making, cyber security and data privacy, and public risk and ethical apprehension towards aspects of biological engineering (see Chapter 8, as well as the discussion in OECD [2016]).

The role of technology diffusion institutions is particularly important in enabling SMEs to upgrade and derive benefits from the transformation of manufacturing. Just as the nature of production is evolving, so should the approach to technology diffusion, as diffusion itself becomes more complex, involves more participants, and occurs over accelerated timeframes and greater scales. This rising complexity must lead to an increased emphasis on networked approaches and renewed efforts to anticipate and address issues of governance in institutions which facilitate technology diffusion. If institutions for technology diffusion can adapt and innovate, taking on roles that address societal as well as economic and technological issues, this could positively contribute to the socially responsible implementation of the next production revolution.

This chapter examines institutions for technology diffusion, their rationale, how they are organised, and the services they provide. Existing and new institutions are discussed, with a focus on publicly oriented mechanisms. The discussion builds on a typology of publicly oriented technology diffusion mechanisms. The typology includes dedicated field services, technology-oriented business services, applied technology centres, technology information exchange, demand-based behavioural change, and open knowledge-sharing. Case studies of selected institutions are presented.

Tested approaches to fostering technology diffusion already exist, such as agent-based intervention, brokering, mentoring, collaborative projects, and referral services, which are able to assist firms in adopting and absorbing new manufacturing technologies and methods. These tested approaches continue to have utility and validity. New approaches are also emerging, including open-source knowledge transfer and community building. Some longstanding institutions that adopt a conventional paradigm of established public programmes to provide services to clients are also able to address new production technologies and take on new functions. Alongside these existing models are new institutions for technology diffusion which typically arise out of emerging technologies and which serve as mechanisms for knowledge exchange, experimentation, and application. Both kinds of institution have important and complementary roles.

The chapter concludes with policy recommendations for strengthening institutions of technology diffusion. In this regard, policy making clearly needs to ensure the integration of technology diffusion and its institutions into the implementation of the next production revolution. There is an inescapable tendency to emphasise exciting research advances and the potential of novel technologies. However, major economic and societal value will only occur if these technologies are responsibly designed and deployed together with users and other stakeholders, and if these technologies can be scaled up, diffused, and improved in use. Indeed, advantages will tend to flow to the companies and systems that are most effective in deploying new technologies and business models. 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. It is important to redress this situation.

Programmes to upgrade existing firms (the majority of firms) must be appropriately resourced, alongside programmes to promote advanced technology development and start-up enterprises. Where institutions for technology deployment are weak or non-existent, they should be reformed, or new institutional capabilities created. Experimentation, learning, the development of relevant new skills and business models should also be encouraged in institutions for technology diffusion. Insights from pilot activities should be incorporated into

existing and new technology diffusion institutions. Similarly, service practices and approaches should be systematically reviewed to ensure that these are effective and customised for the communities served, to ensure knowledge exchange, and to ensure the scale-up of new approaches as needs evolve. Management mechanisms should be developed to reform (or replace) technology diffusion institutions that are resistant to change. There are practices that policy makers should seek to avoid. Perhaps the first of these relates to the inclination to concentrate attention and resources on policies to back research breakthroughs and exciting laboratory technologies and to overlook, or at least poorly support, the industrial scale-up and diffusion of new technologies. Furthermore, efforts to diffuse new technologies often target predictable early adopters. These adopters tend to be large multinationals, high-technology start-ups, and the small number of companies involved in technology development. Policy attention should not just be placed on these likely early adopters, but also on the much larger number of existing SMEs. Indeed, a substantial part of the success of the next production revolution will depend on take-up by SMEs.

Reflecting on the rationale for policies to support institutions for technology diffusion is also important. Such policies should not be pledged as programmes that can restore lost manufacturing jobs. Technology diffusion institutions can help firms today to adjust their business approaches and to adopt new technologies, products, and strategies. Upgrading the ability of manufacturing communities to absorb next production revolution technologies will take time (five to ten years or more). This means that technology diffusion institutions need to be empowered and resourced to take longer-term perspectives.

The systematic and networked nature of many aspects of the next production revolution demands a high level of co-operation among producers, users, and other actors. Firms, suppliers, users, and intermediary institutions should be included in collaborative strategies for diffusion. Accordingly, technology diffusion institutions, which have often worked at an individual project level, now need to adopt strategies and actions that can work in multi-actor collaborations. They also need to address missions of sustainability and responsible research and innovation.

Finally, it is vital to undertake an ongoing review and analysis of organisational designs and models for technology diffusion under the evolving conditions of the next production revolution. In so doing, evaluation metrics should give more weight to longer-run capability development, rather than short-term incremental outcomes. Sharing good practices is also essential. Policy and management approaches should stimulate technology diffusion institutions to upgrade their current methods and to trial promising new approaches as the innovation landscape evolves.

What are institutions for technology diffusion and what do they do?

While technology is a term that is often associated with machines and devices, our understanding of technology has to be broader, encompassing the organisation and application of knowledge for practical purposes.[1] Technology may be embodied, as in machinery, or disembodied, in the form of know-how, methods, and processes. The diffusion of technology can be viewed as the process by which innovations and new technologies disseminate and get taken up.[2] Institutions for technology diffusion are intermediaries, structures and routines that facilitate the adoption, spread and use of knowledge, methods, and technical means, ranging from improving the efficiency of existing production facilities and introducing new process technologies to product development, strategic planning and

training. A technology diffusion institution may combine a tangible presence (e.g. facilities), capabilities (people, expertise, communications), and partnerships (with technology developers and users) alongside "soft" aspects where tacit knowledge is shared via informal interactions (specialists, other companies).

While an innovation system invariably contains multiple sources of technology diffusion, such as universities, professional societies, and the media, the focus in this chapter is on public or quasi-public institutions, or parts of those institutions, that prioritise technology diffusion roles. These institutions are a significant, although at times undervalued, component of the mix of research and development (R&D), technology, business support, human capital, regulatory and related policies that nations and regions use to foster economic development and innovation. Technology diffusion is differentiated from technology transfer, although these two practices are related and can complement one another. Technology transfer implies the conveying of a technology from its developer to a user, with a prime example (in the public sphere) being the establishment in the United States (under the Bayh-Dole Act of 1980) of university and federal laboratory technology transfer offices to license federally funded intellectual property to companies.[3] In this context, technology transfer is the transfer of ownership rights of the outputs from R&D under contractual arrangements between a public organisation and an assignee. Technology diffusion is more embracing in scope and intensity: while it can include technology transfer, it also includes active outreach to firms to assist them to use their existing technologies and processes more efficiently, to provide guidance, expertise and training to upgrade the absorptive capabilities and performance of these firms, and to help diagnose problems and address them, including through applied projects.

Dedicated technology diffusion institutions include industrial extension programmes, technology-oriented business services, applied technology centres, and also university technology transfer offices. Additionally, networks, partnerships, and open-source collaborations are increasingly important in orchestrating technology diffusion. The effectiveness of these institutions depends on the absorption capability of firms for new knowledge and technology services (Cohen and Levinthal, 1990) and to the extent of demand for innovation and new technology (Edler, 2016). Technology diffusion institutions do contribute to efforts to build absorptive capability, e.g. through training, information exchange, and mentoring. Similarly, efforts have been made to facilitate absorption through such mechanisms as innovation vouchers that encourage potential users to engage with knowledge or technology suppliers (OECD, 2010b). In turn, both the development and take-up of new technology is influenced by broader factors in the innovation and policy systems of regions and nations. For example, Hekkert et al. (2007), identify seven interrelated innovation system functions that are critical for understanding the dynamics of technological change: the presence of active entrepreneurship, knowledge development processes, knowledge diffusion networks, search guidance, market formation, financial and human capital resource mobilisation, and orientation to change. Other analysts have highlighted the importance of socio-technical regimes and multi-level frameworks in the elaboration of technological transitions (Geels, 2002).

Innovation systems have particular national characteristics and needs and vary (including at regional levels) in the organisation of their functions. Hence, contrasts can be expected in the design and operation of technology diffusion institutions between and within different innovation systems. At the same time, institutions for technology diffusion, depending on such aspects as their leadership, strategy, scale, and relationships, can

correspondingly have an influence on innovation system functions. This can occur through providing guidance about new technologies, linking companies with sources of finance for manufacturing modernisation, or signposting new market opportunities for innovative product development. Institutions for technology diffusion can also serve as conveners by connecting individual firms with the sometimes myriad and complex array of programmes and providers within multifaceted innovation systems. The relationships of technology diffusion institutions to their host innovation systems can be continuous, in the sense of pursuing tried and tested approaches to technological upgrading and supporting incremental change. The significance of such a continuous role should not be underestimated: SMEs often move slowly in adopting new technologies and, when they do, a step-by-step approach is appropriate from resource, capability, and risk management perspectives. Yet, institutions for technology diffusion may also have to take on discontinuous strategies, developing innovative mechanisms and approaches that are particularly relevant for deployment of major new technologies, particularly where those technologies also require associated socio-technical system changes. For example, in enabling the deployment of automated factory systems, a new partnership of users, vendors, customers, and intermediary institutions may be needed to facilitate new digital design and data sharing systems, address issues of job restructuring and retraining, and introduce integrated management and inventory arrangements.

Rationales for institutional intervention

The major benefits (as well as the consequences) of technological advancement materialise when those technologies are diffused and applied.[4] This is a critical point: policy deliberation on emerging technological transformations often focuses on the future models and exciting innovations in R&D laboratories, and on a handful of promising prototypes. But significant and broad impacts, be they economic, environmental, or societal, will only accrue with diffusion. Moreover, the feasibility and performance characteristics of emerging technologies and associated business models can be advanced where learning from diffusion among users and customers feeds back to developers through iterative design, build and test processes (Fleck, 1997; Govindarajan and Trimble, 2004; Baden-Fuller and Haefliger, 2013).

However, in practice, diffusing technologies is not straightforward: there can be multiple challenges and failures that limit, confound or block the adoption and effective use not only of leading-edge but also current best-practice manufacturing technologies and methods. This in turn can lead to sub-optimal performance in terms of critical manufacturing process variables, such as productivity, quality, yield, waste, energy use, response time, feasible batch size, and costs, and also in terms of capabilities to design and develop innovative products and add value to users and customers (Box 7.1). Sub-optimal manufacturing performance not only impacts individual firms (including ultimately their survival) but also can have adverse effects on industrial supply chains and sectors, regional clusters, and national economic competitiveness, and serve as a constraint on the ability to afford, absorb and deploy new technologies and methods. The challenges and consequences of lags in industrial upgrading are especially evident among existing manufacturers, particularly SMEs (NAPA, 2003; National Academy of Engineering, 2012). For example, results from the US Census of Manufacturers, conducted every five years, suggest that value-added per employee in SMEs (defined as manufacturers with fewer than 500 employees) has generally been 60% of that of their larger counterparts over the 1992-2012 period (US Census Bureau,

2016). The OECD report *The Future of Productivity*, which compares manufacturers in multiple countries, finds a significant gap in the labour productivity growth of manufacturers between a leading set of frontier firms and the majority of non-frontier firms. Frontier firms, which tend to be larger, more profitable, and younger, enjoyed average annual growth in labour productivity of 3.5% compared to 0.5% for non-frontier firms between 2001 and 2009 (OECD, 2015). The diffusion of technologies and techniques, which includes enhancing the capacity of firms and their supply chains to re-engineer their systems, can help to raise productivity levels. The McKinsey Global Institute estimates that 55% of potential productivity gains in developed countries comes from catching up to best practice, with 45% coming from pushing the frontier outwards; the potential productivity gain from catching up is even more pronounced in developing and emerging economies (Manyika et al., 2015).

Box 7.1. **Lags in technological upgrading in manufacturing**

Why is it that more manufacturers do not upgrade their technologies and processes to move closer to performance and productivity frontiers? Explanations conventionally focus on a mix of contributory market, public, and system failures. These include constraints in input and process factors, such as lack of access to capital, skills, knowledge, and management capabilities, as well as by information deficiencies and asymmetries. Enterprises (especially SMEs) frequently lack information, expertise and skills, training, resources, strategy, and the confidence to adopt new technologies. Suppliers and private consultants can experience high transaction costs in trying to diffuse technologies to many small firms. Public institutions, such as universities and national research centres, are often focused on publications, leading-edge technologies in laboratories, and high-technology start-ups; existing SMEs often find such institutions complicated and unwieldy to engage with, notwithstanding their increased efforts to be more business-facing. Finance for scale-up and implementation is not always forthcoming, with the risk that companies will under-invest. Moreover, industrial companies have systems, routines, and attitudes that are already operating and embedded. These existing systems are often resistant to change. This may be due to competency traps, where the company has expertise and experience in its current methods and is reluctant to change even if new methods are superior, or because an industry segment or supply chain is "locked in" to an inferior approach due to network effects or behavioural embedding. Importantly, while the continued use of "less than best practices" can be due to legacies, preferences, and the ongoing influence of past investments, such "sub-optimal" path-dependent practices can still be profitable for the immediate term. Yet, in continuing to use these practices, they can constrain moving to higher levels of performance and longer-run capabilities to be competitive while maintaining good wage levels and working conditions. For example, manufacturers may retain older, less efficient capital equipment, particularly in older plants, because it is cheaper in the short run rather than installing new machinery that would enable greater customisation capabilities, energy savings, and data collection and analysis for process improvement (Hagerty, 2013). These supply-side issues can interact with demand-side constraints, where users in intermediate and end markets are reluctant or slow to deploy the products of innovative new technologies, again for reasons such as network failures (e.g. no critical mass of users), information, capital and other system constraints (Geels, 2002; Edler, 2010, 2016).

Public and system failures that constrain industrial upgrading provide core rationales for supporting institutions and mechanisms for technology diffusion. While certain constraints to upgrading can be alleviated through indirect financial instruments, such as

grants, loans, and tax incentives, a central part of the mission of institutions for technology diffusion is the provision of direct guidance and support. This kind of engaged and expert assistance is particularly important in helping to overcome information gaps, breaking down entrenched path-dependent practices, and in assisting firms and value chains to develop upgrading strategies. Support from technology diffusion institutions seeks to guide and support enterprise capabilities and to assist them in justifying and adopting investments in new technology. Technology diffusion institutions can also work with industrial segments or supply chains that are locked in to outmoded approaches and where change requires the stimulation and support of collective action. For example, the maintenance of mechanical processes in manufacturing can be overlooked until there is a breakdown, while companies may avoid making changes in the process because they have stored inventory, which facilitates production continuity but adds cost. Introducing advanced sensors and communications to provide early signals of wear and relay real-time data back to service providers could eliminate this problem, but would require collaboration among machinery makers, users and maintenance service providers to agree on common protocols. A technology diffusion institution could facilitate a solution through a collaborative project and support adoption by lead users, as well as advising on technological options.

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, as potential users are challenged to sift through burgeoning amounts of information and to support decision making in the context of rapidly changing technologies and requirements for expertise. Additionally, there are also likely to be increasingly strong systemic rationales for supporting not only current institutions for technology diffusion but also for developing new ones that reflect the characteristics of emerging production and technological developments. Technology roadmaps such as Germany's "Industry 4.0" and the United Kingdom's Synthetic Biology Roadmap have helped lay out pathways for systemic and pervasive industrial transformations. These scenarios will come to fruition only if diffusion is fully integrated and implemented at scale. However, many existing institutions are geared for the 20th century, when R&D was seen in a linear way, with diffusion tacked on. Intensified considerations of the need for responsibility in innovation and of targeting global challenges raise further system challenges for technology diffusion institutions. In the future, technology diffusion institutions will need more engagement in missions that not only support diffusion to individual firms, but also link to networks of suppliers, users, and customers. These approaches will increasingly need to incorporate mechanisms for the responsible design, integration, and use of emerging technologies.

Types of technology diffusion institutions

In broad terms, as discussed above, institutions for technology diffusion are intermediaries, employing structures and routines that facilitate the adoption, spread and use of knowledge, methods, and technical means. Although institutions for technology diffusion share the general challenge of addressing market, public, and system failures, there are differences in how these institutions are commissioned, organised and operated. These differences reflect not only the mix of specific failures and targets that each institution is tasked to deal with, but also national, regional, and sectoral variations in innovation system landscapes, policies, and practices. Publicly oriented technology diffusion institutions may be managed by, or associated with, universities, government

agencies, and non-profit or for-profit organisations. Their missions may be targeted at transferring leading-edge technologies, deploying known methods to new users, or a mix of these approaches. Again, depending on their mission and orientation, technology diffusion institutions may operate, or be linked with, R&D laboratories, demonstration and training facilities, and exchange and meeting spaces. While technology diffusion will be a primary focus, in many cases technology diffusion institutions engage in a range of activities and partnerships to support their mission, including with other organisations involved in innovation, technology, business, and skills development.

Yet, notwithstanding such multiple combinations in their form and function, it is possible to distinguish categories of these institutions by signature elements of their approach to diffusion and by the modes through which they operate. To illustrate the array of technology diffusion institutions, six exemplary types are identified (Table 7.1). These range from dedicated field services and technology-oriented business services that extend expertise, guidance, and other resources to firms, to applied and advanced technology centres which have the capabilities to undertake business-facing R&D. The typology includes knowledge exchange and demand-based instruments that serve as intermediaries and stimulators for technology diffusion, and also open technology mechanisms which represent new, often virtual, ways to link technology development and diffusion. These six categories are not mutually exclusive: for example, field services are offered by some applied technology centres, while advanced technology centres also engage with knowledge transfer networks. Moreover, this typology is not exhaustive – other categories could be incorporated. However, the range of institutional types encompassed makes it possible to demonstrate the variety of approaches to technology diffusion currently in use, to discern insights about effective approaches and practices, and to consider how these institutions are addressing challenges presented by the next production revolution. The next sections of the chapter discuss these key institutional types in further detail.

Table 7.1. **Typology of institutions for technology diffusion**

Diffusion mechanisms	Operational modes (primary)	Examples
Dedicated field services	Diagnostics, guidance, and mentoring	Manufacturing Extension Partnership (US)
Technology-oriented business services	Advice linked with finance Capacity development	Industrial Research Assistance Program (Canada) I-Corps (US)
Applied technology centres	Contract research, collaborative applied research, prototyping and standards	Fraunhofer Institutes (Germany) Manufacturing USA (US) Kohsetshushi Public Technology Centers (Japan)
Targeted R&D centres	Advanced research on emerging technologies intertwined with commercialisation missions	Campus for Research Excellence and Technological Enterprise (Singapore)
Knowledge exchange and demand-based instruments	Technology community networking Knowledge transfer incentives	Knowledge Transfer Networks (UK) Innovation Vouchers (multiple countries)
Open technology mechanisms	Shared technology library Virtual networking	BioBricks/Registry of Standard Biological Parts (US)

Source: Authors' analysis.

Dedicated field services

Dedicated field services work with SMEs to help them adopt modern, proven manufacturing technologies and techniques using industry-experienced specialists, commonly in an engineering domain. The services are usually organised in a decentralised manner, with specialists working at the manufacturing site on projects aimed at solving the company's problems and needs. Dedicated field services offer varied forms of

assistance, including help with quality systems, lean manufacturing, energy conservation, environmental protection, health and safety, computer systems and software applications, and product development and marketing. These services usually offer assessment of the company in question, the development of an in-depth project, and the tailoring of relevant training. Dedicated field services can provide services in-house and/or refer companies to other providers including private consultants, government programmes, human resource development organisations, and applied research equipment and facilities centres. Operational funds for these services are often based on a mix of client fees and core public support (Shapira et al., 2015).

The US Manufacturing Extension Partnership (MEP) is a dedicated field service programme targeting SMEs. Established in 1989, the MEP evolved throughout the 1990s into a national network of centres in each US state plus Puerto Rico, with each centre often having field offices at different locations around the state depending on the size of the state. Some centres are organised as private non-profit entities, some as non-instructional units of universities, and others as state government programmes. The National Institute of Standards and Technology (NIST), under the US Department of Commerce, administers the MEP. NIST has provided one-third of the funding for these centres matched in a 3:1 ratio with non-federal sources. The federal contribution to the MEP budget was about USD 130 million in fiscal year 2016. In January 2017, the American Innovation and Competitiveness Act changed the federal share of MEP funding to 50%.[5] The centres provide a pragmatic set of services related to process improvement, product development, marketing, training, and sustainability services such as energy conservation and environmental management. Most centres also connect manufacturing SMEs with other private and public assistance sources. Governance is based on a co-operative agreement between NIST and the individual centre. National and centre-level advisory boards also operate, comprised primarily of SMEs. The MEP programme serves 7 000 to 8 000 SMEs nationally through around 12 000 projects. There is an extensive evaluation process composed of customer and activity reporting, independent client surveys, annual reporting, review by expert panels, and special studies, measuring attributable cost savings, sales, capital investment, jobs, productivity and other economic impacts.

Technology-oriented business services

Technology-oriented business services are services designed to help start-ups and small firms by melding business assistance with financial support. They address weaknesses in the links between business technology upgrading efforts and financial capital. Two programmes that exemplify this category are Canada's Industrial Research Assistance Program and the US Innovation Corps (I-Corps).

The Industrial Research Assistance Program (IRAP) was established in the early 1960s by the National Research Council (NRC) of Canada. IRAP is centrally co-ordinated with a decentralised network of field offices and is administered by the NRC (Shapira et al., 2015). The programme uses former executives to work with companies, offers funding for applied R&D projects to SME clients through non-repayable contributions, and collaborates with partner organisations to provide services to entrepreneurs. The programme operates offices at its own and partner organisations in five regions, with most of the offices concentrated in the provinces of Quebec and Ontario. Nearly half of IRAP's annual budget of around USD 90 million supports the advisory services and the rest is used to deliver applied R&D funding. The programme does not charge companies for services. It engages in ongoing relationships with

a portfolio of client firms. IRAP also provides funding to public sector organisations in remote locations to help them to provide services. Roughly 10 000 firms a year are served of which one-third typically receive non-repayable contributions. Eligible companies are SMEs in product-oriented categories, primarily in information and communication technologies (ICTs), materials and manufacturing, construction, agriculture and food, energy and environment, and life sciences. Customers receiving non-repayable contributions must complete status reports and project and impact assessments. In addition, the programme is subject to a legislatively mandated external assessment every five years.

I-Corps is a programme started in 2011 by the US National Science Foundation (NSF) to accelerate start-up activity from science-based research. I-Corps is based on the "Lean LaunchPad" curriculum at Stanford University, developed by Steve Blank (2013). The idea behind I-Corps is to train teams, comprised of an NSF principal investigator, an entrepreneurial lead (typically a student or postdoctoral researcher) and a mentor. The programme employs lean customer discovery techniques – these are systematic methods to understand what customers most value and to test products or services that best address their needs. The training uses Alexander Osterwalder's Business Model Canvas (Osterwalder and Pigneur, 2010), requiring teams to develop a hypothesised business model for one or more applications of their research. Teams are required to leave the laboratory and talk to roughly 100 potential customers and partners about their proposed product or service in the context of the hypothesised business model, making changes (also known as pivots) to this business model in response to the feedback they receive. After a three-day "boot camp" (an intensive short course), possible modifications following the feedback are considered. Each team then makes a choice as to whether or not to pursue the application as a start-up or as a licensing opportunity, known as the "go-no go" decision. Anecdotal evidence from early I-Corps cohorts indicated that a lack of supporting services and infrastructure at their home universities limited cohorts' success. This led NSF to create an ecosystem around I-Corps of what are termed "nodes" and "sites". Nodes are regionally distributed locations at universities that provide training, while sites provide entrepreneurship and commercialisation support at the university to I-Corps teams, often on their home campus to enable team formation. VentureWell, originally known as the National Collegiate Inventors and Innovators Alliance (NCIIA), operates a National Innovation Network, managing a database of I-Corps activity, engaging in community building, and performing ongoing evaluations of the programme. There are no comparison group studies of I-Corps, but initial assessments report a three-fold increase in familiarity with the business model canvas after the training. The NSF budget for I-Corps was USD 30 million in fiscal year 2016 (US NSF, 2016). Team awards of USD 50 000 cover expenses associated with training and customer discovery. Sites receive up to USD 100 000 for three years. Nodes receive USD 2 million to USD 4 million over a three-year period to provide training. Interest in I-Corps has spread to other US federal agencies including the National Institutes of Health, the Department of Energy, the Department of Defense, the Department of Homeland Security, and the Small Business Administration. Similar lean customer discovery methods have spread globally, e.g. to SynbiCITE in the United Kingdom, which uses these methods to accelerate the commercialisation of synthetic biology applications (SynbiCITE, 2016).

Applied technology centres

Applied technology centres conduct contract R&D for companies, state and local governments, and other types of organisations. Applied technology centres can be part of

larger comprehensive organisations. A prominent example is the Fraunhofer Society – a private non-profit network of about 60 research institutes in Germany that carry out contract research for the government (at national and state levels) and business organisations (Fraunhofer, 2016). Established in 1949, the Fraunhofer Society falls under the German Ministry of Education and Research but largely manages its own operations. Each Fraunhofer institute specialises in a particular technology or sector. The institutes use a mix of in-house researchers and students to perform their research. Services include joint pre-competitive research, bilateral applied research with individual firms, prototyping, and pre-production and co-operative technology transfer arrangements. Fraunhofer services tend to be large, highly customised, high-value projects. One-third of the Fraunhofer budget comes from core institutional sources in amounts exceeding USD 700 million. The remainder of the budget derives from work with private industry and public sector agencies. Fraunhofer institutes can provide services to clients outside their regions and there are institutes located in the United States under the aegis of Fraunhofer USA. The institutes produce publications, patents, research contracts, licences, and start-up companies. Other groupings of applied technology centres include TNO in the Netherlands, the GTS Institutes in Denmark, SINTEF in Norway, and Technalia in Spain (Solberg et al., 2012; Shapira et al., 2015).

Manufacturing USA, formerly known as the National Network for Manufacturing Innovation, is an initiative to develop a Fraunhofer-like system in the United States focused on applied research and the commercialisation of key manufacturing technologies (US NNMI, 2016). The network is comprised of institutes anchored by a private non-profit organisation. The first institute, dealing with 3-D printing, was founded in Youngstown, Ohio in 2012. Core funding for the institutes comes from various agencies, depending on the mission of the institute, including the Department of Defense, the Department of Energy, the Department of Commerce, the National Aeronautics and Space Administration, and NSF. Core multi-year funding of some USD 60 million is matched by a mix of sources, including memberships for multinational and smaller private sector companies, universities, and non-profit organisations. Membership benefits include royalty-free access to intellectual property (IP) depending on the organisation's membership fee level, participation in institute R&D projects, and influence on the research agenda of the institute. Many of the institutes deal with significant standards issues, particularly in efforts to manufacture products involving complex systems. For example, one of the projects of the Digital Manufacturing and Design Innovation Institute is to develop a digital manufacturing commons for data sharing, analysis, modelling, tooling, and building. Being able to draw on the expertise of a membership consortia facilitates this institute's ability to marshal input and participation from the relevant community (DMC, 2016).

Targeted R&D centres

While applied technology development centres focus on business-oriented projects, driven by high levels of business engagement and governance, targeted R&D centres are driven largely by researchers themselves with a mission of leading-edge emerging technology research combined with a mandate to generate economic impact. Increasingly, such centres are also tasked with tackling societal challenges through the development and diffusion of their targeted technologies. Targeted R&D centres are typically located at universities, with significant support for their research themes provided by government research sponsors pursuing policies to advance specific emerging technologies that are anticipated to have significant economic and societal impacts. There has been increased

and more explicit consideration of such economic and societal aspects in several recent flagship R&D initiatives in emerging technology domains. Among national examples, NSF has sponsored 17 Nanoscale Science and Engineering Centres in the United States, each in specific areas of emerging nanotechnology, under a framework (the 21st Century Nanotechnology Research and Development Act[6]) that emphasised not only advanced research but also the incorporation of new technologies into products, the development of skills and tools, and responsible development (Fisher and Mahajan, 2006; Rogers, Youtie and Kay, 2012). In the United Kingdom, six Synthetic Biology Research Centres have been sponsored under a national programme to advance research capacity, foster industrial linkages and the commercialisation of synthetic biology, develop training, and promote attention to responsible research and innovation (UK Synthetic Biology Roadmap Coordination Group, 2012; Shapira and Gök, 2015).

Targeted R&D centres can involve multiple universities and other stakeholders, and multi-institutional approaches often involve international relationships. Singapore's Campus for Research Excellence and Technological Enterprise (CREATE) is one such approach that combines targeted research and commercialisation with international partnerships.[7] Developed by the Singaporean government, CREATE uses research partnerships between Singapore's two major research universities and ten prestigious research universities in the United States, Europe, the Middle East, and Asia to develop new production technologies linked to the city-state's major societal challenges (CREATE, 2016). CREATE began in 2006 under the auspices of the National Research Foundation of Singapore. CREATE established a USD 250 million research facility adjacent to the National University of Singapore (NUS) University Town (UTown) campus in support of this research. In addition, each foreign partner university received roughly USD 100 million to perform the applied research, 75% to 80% of which is allotted to the Singaporean university partner – typically NUS or Nanyang Technological University (NTU) – for researchers and equipment. The research university arrangements have been structured to last for a five-year period, renewable for an additional five years.

The programme originally designated ten foreign universities as collaborators: the Swiss Federal Institute of Technology, Zurich; the Massachusetts Institute of Technology (MIT); the Technical University of Munich; the Hebrew University of Jerusalem; Ben-Gurion University; the University of California, Berkeley; Peking University; Shanghai Jiao Tong University; and Cambridge University. Each research project involves two senior investigators: one usually from NTU or NUS (although other Singaporean universities may participate) and the other from the foreign partner university. The projects fall into four interdisciplinary areas: human systems (such as tropical and infectious diseases), environmental systems (such as water management), urban systems (such as driverless vehicles), and energy systems (such as building efficiency). The programme uses several mechanisms to ensure that commercialisation is established in Singapore. Each partner university must establish a Singaporean limited liability company to receive and manage the research funds. All foreign university research centre directors must be based in, or spend the majority of their time in Singapore, while all senior investigators of the partner universities must adhere to a one-year residency requirement in which at least six consecutive months are spent in Singapore. Additionally, the Singapore Technology Licensing Office manages all IP. Management of the programme involves key performance indicators mutually agreed to by the National Research Foundation and the foreign university.

Knowledge exchange and demand-based instruments

Increasing attention has been paid in recent years to the development of intermediary institutions to facilitate technology diffusion processes. There has also been an expansion in the role of demand-side instruments that can incentivise firms to initiate interactions with technology diffusion intermediaries and with sources of technology on the supply side. Such "boundary-spanning" mechanisms are recognised as being vital to the iterative brokering, mediation, and diffusion of knowledge about new technologies and methods among and between firms and research and technology organisations (Aldrich and Herker, 1977; Tushman, 1977; Kaufmann and Tödtling, 2001; Virani and Pratt, 2016). There are many varieties of these mechanisms, with the growth not only of technology transfer networks but also knowledge exchange and co-production networks, and the increasingly inventive use of behaviour-oriented incentives to encourage firms to cross boundaries to learn about new approaches.

Explicit public policies to foster networks among firms to advance innovation through information exchange and collaboration began in Italy in the 1970s, extending to Denmark in the 1980s, and to many other OECD countries in subsequent years (Cunningham and Ramlogan, 2016). A current example is the United Kingdom's Knowledge Transfer Network (KTN), a mechanism funded by the publicly sponsored innovation agency Innovate UK. KTN supports networks of companies, universities, investors, non-profits and other interested actors to exchange and collaborate in targeted areas of technology. Specialist KTN staff serve as catalysts for network activities, which currently cover activities in 16 key sectors including biotechnology, creative industries and the digital economy, manufacturing, materials, and sustainability and the circular economy. The KTN also brings together about 20 special sectoral interest groups, on such topics as the flexible manufacturing, energy-efficient computing, robotics, and synthetic biology.[8] The KTN delivers its activities through facilitating online exchanges among network members, organising open events, collaborating with knowledge centres (e.g. in materials chemistry or process innovation), facilitating access to funding competitions, and organising taskforces and roadmaps. In 2015-16 KTN reported more than 77 000 members, over 400 events involving in excess of 20 000 participants, more than 120 roadmaps and analyses, many thousands of individual meetings, and assistance with 455 funding proposals and about 120 funding events. The annual budget of the KTN is about GBP 15.8 million.

Knowledge exchange networks typically bring together participating members within and across a value chain of interest, e.g. developers and potential users of an emerging technology, or firms and technology organisations engaged in a particular sectoral supply chain. Such networks can be national or international, but they can also have regional dimensions. Where there is a strong regional dimension to technological knowledge exchange, networks may merge with, or evolve into or from, cluster initiatives that broadly link agglomerations of firms and other innovation system actors within particular geographical localities. In Germany, more than 450 regional cluster networks have been identified, many sponsored by federal and state government alongside other privately led clusters (Clusterplatform Deutschland, 2017). Active technological sectors (with the number of regional clusters as of January 2017) include the environment (79), energy (69), information and communications (69), production (66), materials (48), the automotive industry (41), biotechnology (41), and electrical engineering, measurement, and sensors (34).[9] These cluster networks support firms to engage with other firms and institutions in technology development and diffusion activities and to link these to new product development,

marketing, and internationalisation strategies. One of the spurs to the development of this dense and diverse array of exchange networks was the Kompetenznetze (Competence Networks) programme, established in the mid-2000s by the then Federal Ministry of Economics and Technology. This programme encouraged the formation and recognition of more than 100 regional networks, including in life sciences, food processing, medicine, renewable energy and information technology, in locations throughout Germany (BMWi, 2010). In 2012, this programme was amalgamated into the German cluster platform jointly sponsored by the Federal Ministry for Economic Affairs and Energy (BMWi) and the Federal Ministry of Education and Research (BMBF). As part of this platform, BMWi sponsors a "go-cluster" programme that provides for a cluster certification procedure, access to public funding, participation in cross-network activities, and guidance from an external support agency. There are about 100 designated go-clusters in Germany, involving some 13 000 members including 8 500 companies, mostly SMEs, as well as universities, Fraunhofer Institutes, other non-university research and technology centres, and business organisations. A recent evaluation finds that linking together these complementary resources with firms through regional network clusters has encouraged the generation and implementation of innovations (Ekert, Schüren and Bode, 2016).

In these and similar networks, key practices include shared industrial, technological, or regional interests, open membership, core capabilities to foster information exchange, collaborative activities, and projects, a business orientation towards translating and deploying future-oriented technologies, and effective governance and management (see also BMWi, 2010; Cunningham and Ramlogan, 2016). Knowledge exchange networks can also take on functions related to co-production, where companies working often with technology institutions jointly undertake development projects and pool design, production, training, and marketing tasks typically among a spatially proximate cluster of network members. Smart city and industry networking programmes have been initiated in several European countries and elsewhere. One example is Brainport Eindhoven in the Netherlands where leadership, increased knowledge exchange and new co-production interactions have stimulated revival in an old industrial port region (Horlings, 2014). An initiative sponsored by two United Kingdom research councils is exploring opportunities for "redistributed manufacturing" where advanced manufacturing technologies deployed in localised and clusters of flexible firms can offer a competitive and sustainable edge over conventional globalised supply chains (Pearson, Noble and Hawkins, 2013). Promising cases are being explored by these networks, including in health care and medical products, and in consumer goods and big data, while other networks are examining the potential gains to redistributed manufacturing of 3D printing and makerspaces (Freeman, McMahon and Godfrey, 2016; Moreno and Charnley, 2016; Zaki et al., 2017).

A complementary mechanism to these knowledge exchange intermediaries and initiatives is the use of incentives to foster demand-side interest and stimulate new boundary-crossing relationships that can accelerate technology diffusion among firms, especially SMEs. Such incentives can take the form of innovation vouchers that SMEs can use to purchase time and other assistance from research and technology institutions and other vendors of business assistance. These combine matchmaking with modest financial incentives to stimulate interest, demand, and behaviour change in enterprises to encourage interaction with universities, research organisations, specialised consultants, and other sources of technology and knowledge (Bakhshi et al., 2015). Innovation vouchers are promoted at both national and regional government levels. Innovation vouchers have been

sponsored in the Netherlands, Ireland and the United Kingdom (among more than 20 European countries underwriting innovation voucher schemes) as well as in Australia, Canada, the People's Republic of China (hereafter "China"), India, Singapore, and the United States (DG ENTR-Unit D2, 2009; Langhorn, 2014; CORFO, 2016). The value of the incentive is usually small (ranging from about EUR 3 000 to under EUR 10 000) and may require a cash or in-kind match from the SME. The incentive is not meant to subsidise the cost of a major project: it generally can support just a few days of time. Rather, the voucher is designed as a behavioural inducement to encourage SMEs to talk with people in other organisations to explore new technological and business options, to undertake initial work, and to scope follow-on steps and project options. Innovation voucher schemes may be targeted to eligible SMEs in certain sectors (e.g. in manufacturing or advanced services), emphasise particular technologies (including ICT), or aim to foster links with specific domains of academic or private sector expertise. Although vouchers by themselves are not sufficient to completely alter how SMEs approach innovation, available evaluations (including with randomised control) suggest that innovation vouchers encourage firms to initiate new relationships and projects (Cornet, Vroomen and van der Steef, 2006; OECD 2010; Sala, Landoni and Verganti, 2015; Bakhshi et al., 2015). Good practices associated with innovation voucher schemes include effective public management, well-organised brokering to link firms with sources of expertise, minimal administrative burden on participants, suitable marketing, and capabilities to initiate follow-on projects (OECD, 2010b).

Innovation vouchers are one example of the demand-side instruments that can be used to foster the diffusion of technology. Other instruments include the targeted use of public procurement, tax incentives and other subsidies to lower the cost of new technologies for users, awareness raising, training, the fostering of interactions between users and producers, and regulation that supports the deployment of new technologies (Blind, Petersen and Riillo, 2016; Edler, 2016; Uyarra 2016). Some of these are "soft" mechanisms that use indirect, informational, or behavioural approaches, while others involve direct financial support. If policy seeks to accelerate the diffusion of the technologies associated with the next production revolution, it is likely that such demand-side approaches will need to be increasingly integrated into, as well as delivered alongside, the activities of institutions for technology diffusion.

Open technology mechanisms

Open-source methods of diffusion of new production technologies have emerged in recent years, mirroring the rise of open-source developments in the software industry. An example is the BioBricks Foundation, which was founded in 2006 by Stanford University professor Drew Endy.[10] A private non-profit foundation that is pioneering open-source models of technology transfer in synthetic biology, BioBricks seeks to overcome the danger that this emerging field will be dominated by IP protection and secrecy, which could then hold back application, diffusion, and further development. BioBricks has created several programmes to foster open innovation in the field of synthetic biology. OpenWetWare is a wiki application that began in 2007 for sharing information among laboratories around the world about protocols and courses and other information relevant to the synthetic biology community. OpenWetWare has more than 20 000 users. Following a foundational synthetic biology conference held at MIT in 2004, BioBricks sponsors a global synthetic biology conference (SBx.0) for community building, alternating between locations in the United States, Europe, and Asia. The most recent was SB6.0 held at Imperial College in the United Kingdom

in 2013 (with more than 700 attendees). SB7.0 is in Singapore in 2017. In 2008, BioBricks began a "request for comment" process that has led to a technical standards framework for standard biological parts to enable these parts to "fit" with one another as they are exchanged. BioBricks has developed a voluntary researcher agreement – the BioBricks Public Agreement – to set out the conditions under which users could employ biological parts. Since 2015, the organisation has promulgated an Open Materials Transfer Agreement (OpenMTA) to address weaknesses in current materials exchange agreements such as limits on commercial participation. Also underway is bio.net, a peer-to-peer information technology platform aimed at enabling the monitoring and exchange of biomaterials.

The BioBricks Foundation was funded with small grants from the US NSF and National Institutes of Health until 2015, when it received a three-year USD 3.9 million grant from the Helmsley Charitable Trust's Biomedical Research Infrastructure Program to create bio.net (Helmsley Charitable Trust, 2016). This funding enabled BioBricks to hire a managing director, a legal and technology transfer director and a software specialist, while enabling it to subcontract software development to Stanford University. BioBricks is starting a membership programme to provide long-term funding.

BioBricks also has a relationship with the International Genetically Engineered Machine (iGEM) Foundation and the International Open Facility Advancing Biotechnology (BIOFAB). iGEM began as an MIT class in 2003 taught by Endy and other colleagues and was designed to teach students to develop biological devices. Randy Rettberg, then an MIT researcher and one of the initial BioBricks board members, spun off iGEM as a separate foundation and now serves as its president. iGEM runs the iGEM Competition for student-based teams to develop devices from standard biological parts (and which also requires consideration of risk and societal implications). IGEM also operates the Registry of Standard Biological Parts, which is used by the student competitors and others to advance innovation in synthetic biology, and the Labs Program, which provides access to biological parts to students outside of the competition. In 2015, the iGEM Competition had more than 5 000 participants in more than 200 international teams. BIOFAB is a production facility developed to design and produce more curated, higher-quality standard biological parts for public sharing. BIOFAB is sponsored by the US NSF and is a partnership of BioBricks, the Synthetic Biology Engineering Research Center at Berkeley, and Lawrence Berkeley National Laboratory. The biological parts are available in a "library" to academic groups and companies, leveraging the BioBricks public agreements to specify the terms for use of these biological parts.

In addition to multiple open-source software platforms, other open technology mechanisms have been formed in such areas as robotics, manufacturing hardware, and operational standards for automation in industry. As technologies and production systems become increasingly sophisticated, integrated, and data-driven, such mechanisms are likely to become increasingly important to foster large-scale co-ordination among multiple organisations. Additionally, open technology mechanisms offer flexible and relatively low-cost pathways for both new entrants and incumbents seeking to scale-up and diffuse emerging technologies.

Institutions for technology diffusion: Trajectories of change and challenges

Institutions for technology diffusion operate broadly across the innovation systems landscape, with varied targets and diverse organisational forms and functions, as the examples above illustrate. Some institutions for technology diffusion are long-established and deeply embedded in their respective innovation systems, while others are evolving or

newly emerging. In the context of the next revolution in production, new institutions will be needed to creatively promote knowledge exchange, organisational change, capacity development, and demand for technology diffusion in emerging technological areas and in new business models. At the same time, it is also important for established institutions for technology diffusion to upgrade and orient their approaches to address the specific challenges and opportunities presented by next-generation technologies.

Institutions for technology diffusion are part of larger systems of innovation; how technology diffusion institutions contribute to, relate with, and leverage their larger systems will depend on the structures and policies enacted in host environments. At a broad policy and system level, a range of relevant factors influence the performance of technology diffusion institutions. These include policies and practices for R&D, university-industry collaboration, finance for business investment, skills, labour markets, infrastructure, IP, trade, fiscal, and macroeconomic policy, as well as the level of system attention to technology diffusion policies (OECD, 1998; Bozeman, 2000; OECD, 2015; Kochenkova, Grimaldi and Munari, 2016; Caiazza and Volpe, 2017). An essential task, through attention to policy mix (Flanagan, Uyarra and Laranja, 2011), is the co-ordination of innovation system framework policies and indirect mechanisms with policies towards institutions for technology diffusion. In particular, both broader frameworks and specific policies should encourage meso- and micro-level strategies that can ensure the effective design and operation of technology diffusion institutions. Here, a series of good practices have been identified. These are raised in the case examples and also further discussed in other studies (see e.g. Shapira et al. [2015]).

An essential good practice is an organisational setting which supports capable management of institutions for technology diffusion. As discussed, the organisational settings for publicly-oriented institutions for technology diffusion can include universities, technology centres, economic development and government agencies, and non-profit corporations. Organisational settings vary according to the innovation systems landscape in different countries, and developed systems can have multiple organisational arrangements that may be centralised or decentralised. The key point, however, is to ensure that whatever organisational arrangements are employed, they enable effective operations, which also means that there should be arrangements for both internal and external performance reviews that can prompt adjustments in services and management, and where necessary, modifications to the organisational setting. Other relevant meso- and micro-level practices for technology diffusion institutions include an explicit client base of firms (which could be broadly across sectors or targeted to specific industries), sufficient programme scale to reach significant numbers of firms within this base, and a structured approach to services to optimise available resources. Additional good practices for technology diffusion institutions include the use of personnel with industrial experience, links to other facilities and service partners, and a base of core funding to ensure stability. In developed industrial and technological ecosystems, there may be multiple institutions for technology diffusion with distinct missions. Across this system landscape, capabilities are needed to upgrade existing firms (typically SMEs) to current levels of technological modernisation, as well as to enhance leading-edge technological capabilities in existing and new firms where that is appropriate, and to work with firms through individual, group, and network modes (Park, 1999; Shapira et al., 2015).

It is critical that institutions for technology diffusion, and their host innovation systems, establish approaches that match current good practices. If there is currently an

effective base for technology diffusion, institutional adaptations and innovations to diffuse emerging technologies can build on this. If the current base is weak, renewed efforts to upgrade and initiate technology diffusion institutions may be required. In either case, institutions for technology diffusion will need to take on board what is known about effective policies and practices. They will also have to adapt and innovate to reflect characteristics that may be accentuated in, if not drive, the next revolution in production. This will help to ensure that institutions for technology diffusion are fit for purpose, as the technological, industrial, and governance context for their operations changes with the next revolution in production.

As noted in the opening parts of this chapter, key features of the next production revolution include the transformative role of ICT, the rise of digital manufacturing, far-reaching changes in materials and economic foundations, and the emergence of new business models with a greater emphasis on user engagement, sustainability, and responsible innovation (OECD, 2016). Of course, attempts to foresee future developments in technology, business, and policy inevitably have to be qualified, as the next revolution in production could unfold in multiple ways. With that caveat in mind, and building on case examples discussed in this chapter and on broad insights from the literature, eight key aspects of technological, economic, and policy change are identified that are intrinsic to the next revolution in production. These should be considered by technology diffusion institutions and policy makers (Table 7.2). These aspects of change, with examples, are discussed below.

Table 7.2. **Technological, economic and policy changes associated with the next production revolution and implications for technology diffusion institutions**

Change aspect	Implications for technology diffusion institutions
Digitalisation	Integrate diffusion of digital technologies in all aspects (including design, materials, production, products, communication, services).
Iterative and rapid emergence of new technologies and business models	Mobilise capabilities for rapid and customised responses. Adapt and innovate organisational business models to reflect new needs and opportunities. Move from project models and formal planning approaches to flexible methods, more group assists, greater sharing.
New capability requirements	Build up capabilities of firms and local innovation ecosystems for technology absorption. Enhance capabilities of institutions in emerging technologies and their integration.
Increased role for collaborative technology partnerships	Bring together multiple actors, including universities, research centres, and private sector organisations to collectively address research translation, scale-up and technology deployment.
Global rise of new knowledge clusters	Develop boundary-crossing and international linkages and partnerships.
Vital importance of sustainability	Embed longer-term considerations of environmental sustainability in technology approaches.
Growing attention to responsible research and innovation	Embed attention to responsible research and innovation in technology approaches.
Catalytic roles for policy and government	Leverage policy and government support through catalytic roles, partnerships and demand-side stimulation.

Source: Authors' analysis.

- **Digitalisation.** Digital information technologies will be at the core of future technology development and adoption. Analogous to the rise of open sharing of research articles and data is the emergence of libraries promoting sharing of technology building blocks. An example already highlighted is BioBricks, which promotes an open-source standard first developed at MIT to enable sharing and enhance usage of synthetic biology parts through the Registry of Standard Biological Parts. The registry is populated primarily with submissions from the iGEM Competition, although a more specialist and higher-quality

public library, BIOFAB, has also been established. These open-source mechanisms exist against a backdrop of traditional proprietary biotechnology approaches. Likewise, the Digital Manufacturing and Design Innovation Institute, part of Manufacturing USA, is using a digital commons approach for development of manufacturing software tools. These examples highlight the burgeoning roles of institutions for technology diffusion not only in diffusing and helping to integrate digital technologies into individual manufacturing companies, but also in developing new collaborative and virtual models across industry sectors and networks to accelerate the use of innovative digital approaches.

- **Iterative and rapid emergence of new technologies and business models.** Institutions for technology diffusion have conventionally adopted linear, project-based models of interacting with companies, often based on formal planning approaches and systematised procedures. While such approaches are likely to continue as a standard for working with enterprises, it is anticipated that the next revolution in production will stimulate, and require, institutions for technology diffusion to increasingly take on more flexible, discovery-based, approaches. A related implication is the need to mobilise capabilities for rapid and customised responses, to increase the pace and relevance of technology diffusion approaches. Signals are already apparent that institutions for technology diffusion are grasping these challenges, with the growing role of flexible and customised methods, more group assists, and greater emphasis on collaborative iteration. An example is the I-Corps programme, established by the US NSF and now increasingly disseminated by other agencies and organisations. I-Corps accelerates the commercialisation of science-intensive research using training influenced by "lean customer discovery" and "business model canvas" concepts. Teams of researchers and budding entrepreneurs are encouraged by programme mentors to undertake ongoing and reflexive interactions with customers and partners. These flexible interactions encourage the early reshaping of technological and business models to meet market demands and opportunities (Weilerstein, 2014). BioBricks, in encouraging collaborative exchange, learning and sharing in its community, is also fostering an iterative approach.
- **New capability requirements.** An essential feature of the next production revolution is not just the emergence of new technologies and business models, but also the convergence and integration of these technologies and business models. For example, digital and physical technologies will increasingly be amalgamated, e.g. in the software engineering of new biomaterials, while fusions of design, manufacturing, logistics and services are expected. Producers will need to acquire new skills in emerging technologies and in the systematic integration of these technologies, as well as in such areas as industrial networking and co-production. In turn, technology diffusion institutions will need to enhance expertise in emerging technology domains and their integration, and pursue strategies that will assist in upgrading the absorptive capabilities of firms and their industrial ecosystems to engage with the next production revolution. Technology diffusion institutions can address these capability challenges in several ways. In the US MEP initiative, attention is paid to internal staff training and human resource planning, with centres also employing flexible arrangements to use third-party service providers who can be varied as technical needs change. In Germany, the Fraunhofer Society and its institutes offer a range of advanced training programmes to business including in new technologies. Fraunhofer and its institutes also transfer knowledge through extensive collaborations with companies, and supports its researchers to spin out and set up their

own companies. Additionally, the close relationships of Fraunhofer institutes with universities facilitates the engagement of early-career researchers in projects with companies: this brings new technical skills into projects and subsequently aids diffusion as these early-career researchers gain expertise in industrial applications and subsequently take up positions with companies. The US I-Corps Sites programme offers universities a new structured and supported method for research commercialisation: this franchising model represents a further way of scaling up capabilities for new approaches to technology diffusion.

- **Increased role for collaborative technology partnerships.** Collaborative partnerships (in the context of technology diffusion) involve the bringing together of multiple actors, including universities, research centres, and private sector organisations, to collectively address tasks of applied research, translation and technology deployment. While such partnerships have a long tradition, next-generation production technologies have stimulated the rise of new partnerships that cross sectoral boundaries and which are designed to address the "scale-up" gap between research and commercial production. These technology partnerships also provide opportunities for tacit as well as formal knowledge exchange, the pooling of capabilities and specialties, agreement on common protocols, and leveraging sponsorship sources through calls for private funds to match public funding. An example is Manufacturing USA, which 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 additive manufacturing and digital manufacturing and design. Partnerships typically have a specific emerging technology focus, as in the case of Manufacturing USA which in early 2017 links 14 manufacturing innovation institutes, with each institute formed from multiple public and private sector partners and concentrating on a particular advanced technology.[11] Similarly, in the United Kingdom, a network of 11 Catapult Centres established through Innovate UK seeks to transform leading-edge research into new products and services, again with each centre composed of multiple partners from the university, public, and business sectors and combining a mix of public and private revenues.[12] Collaborative technology partnerships may be organised through national networks and initiatives, but they often have important regional dimensions and may involve international partners and partnerships (as discussed below). The next production revolution will probably demand the greater use of collaborative partnerships for technology diffusion to systematically address the translation of complex emerging technologies and to draw on both public and private resources.
- **Global rise of new knowledge clusters.** The next production revolution will mobilise a range of clusters of knowledge and innovation around the world. These include locations in developed economies in Europe, North America, and East Asia, but also in rapidly emerging economies. In China, new initiatives are underway to upgrade manufacturing, with a focus on innovation and advanced manufacturing technologies.[13] In multiple city-regions in China, including in Beijing, Shanghai, and Shenzhen, there are substantial clusters of leading-edge research, companies and entrepreneurs actively engaged in innovative manufacturing approaches (Bound et al., 2016; Saunders and Kingsley, 2016). Dynamic regional innovation clusters have grown or are emerging in India, Brazil, and other parts of the world (Dutta and Lanvin, 2013; Engel, 2014). Institutions for technology diffusion have generally operated within national and regional jurisdictions, although some institutions have established international locations. Fraunhofer Institutes have developed locations outside of Germany, in part to offer services to German-managed

global supply chains but also to access specialised technological expertise in other countries. In addition to operating branded centres abroad, another strategy is the involvement of international organisations and companies not as clients but as partners in technological collaboration and diffusion. For example, the United Kingdom's Cell and Gene Therapy Catapult has reached an agreement with the Kanagawa Prefecture of Japan to foster the application and commercialisation of regenerative medicine and cell therapy in both Japan and the United Kingdom, which includes facilitating market access for British firms in Japan, and for Japanese firms in Britain and Europe.[14] As discussed earlier in the chapter, Singapore's CREATE programme partners with domestic and foreign universities to facilitate research capacity development and commercialisation in applied areas that address societal challenges facing the city-state such as urban congestion, tropical diseases, and access to energy sources. As knowledge and innovation clusters rise around the world, institutions for technology diffusion will increasingly need to find ways to access and engage in knowledge and technological exchange with counterparts in these locations.

- **Vital importance of sustainability.** Sustainability is an increasingly important feature of next-generation production. Indeed, many aspects of next-generation production, such as the deployment of biomaterials to replace petrochemicals, the use of nanotechnologies in more efficient renewable energy solutions, and the development of redistributed manufacturing approaches that reduce transportation requirements, promise greener and more sustainable processes and products. These should contribute to addressing global challenges related to the environment, energy, and greenhouse emissions. Yet, in addition to addressing global goals, attention to sustainability can return benefits directly to companies and consumers, through reducing waste and materials usage, lowering life-cycle costs, and prompting process and product innovation. In the United States, the MEP offers services to assess energy usage and put forth recommendations for reduced consumption, to identify process improvement opportunities, and to assist with compliance with environmental regulations. This assistance includes compliance with energy standards such as the energy management standard ISO 50001 and environmental management standards in the 14000 series. At a wider level, the United Kingdom's Energy Systems Catapult helps firms to develop and capture commercial opportunities across the energy system.[15] Attention to environmental sustainability is likely to be a growing feature of technology diffusion activities in the next production revolution.[16]
- **Growing attention to responsible research and innovation.** Responsible research and innovation aims to anticipate the societal, ethical, and legal, as well as the environmental, health and safety implications of new science and technology. It also seek to avoid or modulate adverse effects, and foster inclusive approaches to, and outcomes from, research and innovation (EU, 2012; Owen, Stilgoe and Macnaghten, 2012). Particularly in Europe and the United States, attention to processes of responsible research and innovation, especially in emerging technologies such as nanotechnology, synthetic biology, and digital technologies, artificial intelligence and automation, has increased in recent years (Owen, Bessant and Heintz, 2013; McBride and Stahl, 2014; Gregorowius and Deplazes-Zemp, 2016; Michelson, 2016). Such technologies comprise core technologies of the next production revolution. Technology diffusion institutions, alongside other public and private actors involved in the next production revolution, will need to embed and operationalise processes of responsible research and innovation in their activities. While this involves awareness of relevant laws, regulations, and protocols, including at

international and national levels, responsible research and innovation is much more than a compliance task. It involves (to draw on a United Kingdom framework) processes of anticipation – of potential economic, social, and environmental impacts; reflection – on implications, motivations, uncertainties and dilemmas; engagement – opening up deliberation and dialogue; and action – to influence the research and innovation process.[17] Attention to responsible research and innovation in the UK Synthetic Biology Roadmap, and its subsequent embedding in the United Kingdom's Synthetic Biology Research Centres, offers an implementation example. The critical issues that arise as responsible research and innovation is operationalised will depend on the technology. For example, in deploying new information technologies in companies and in networks of producers and users, there will need to be attention to data protection, privacy, and security. New medical technologies may raise complex ethical issues. Life cycle and environmental factors need particular consideration in the application of new renewable energy technologies. However, across the range of technologies involved in the next production revolution, all raise economic, social, and environmental issues in one form or another. One common concern is about equity considerations in dealing with displacement effects of emerging technologies on segments of the population that might lose their jobs or see their jobs transformed. At broad levels, institutions of technology diffusion have an important role in working with technology developers, policy makers, companies, publics, and others in their communities to encourage early consideration of responsibility in research, design and initial development. Additionally, in the deployment of specific technologies, institutions for technology diffusion should build specific steps and actions into projects and service plans for responsible innovation to ensure attention to any adverse effects and seek to avoid or mitigate potential difficulties. An example of how this might be done for the I-Corps programme raises a set of public value questions that teams can ask as part of their discovery process (Youtie and Shapira, 2016).

- **Evolving roles for government.** It is common to look to government, usually the national government, as the director, manager and source of funding for institutions for technology diffusion. This role for government endures, since without public intervention and funding, market failures will lead to under-investment in technology diffusion, as discussed earlier in this chapter. In particular, in national innovation systems where institutions for technology diffusion are currently weak or disorganised, direct public intervention and sponsorship is likely to be necessary to promote upgrading and effective service delivery. Yet, building on a broader movement that began some years ago to deliver public policy through other mechanisms, such as public-private partnerships, the next production revolution will raise needs and opportunities to further evolve government roles in fostering technology diffusion. Policies to support technology diffusion as part of the next production revolution will involve the fostering of roles and agents that serve as catalysts, brokers, and stimulators to engage other public and private organisations to collaborate and leverage resources and to join together to pursue pathways for new technology adoption and responsible innovation. Manufacturing USA, as already mentioned, represents an approach in which non-profit organisations in the United States must partner with private industry, universities, and other non-profits through membership arrangements. This helps to secure funding, but most importantly brings together the portfolio of expertise and capabilities required for advanced technology scale-up and deployment. Attention to spanning the policy mix in the diffusion of next-generation technologies will demand the greater engagement of actors that can help to

address financial, information security, regulatory, environmental, human resource and societal requirements. Piloting creative new approaches and institutions for technology diffusion, especially in key emerging technologies, will be vital, as will a willingness to experiment and foster discovery and iteration of new methods. Additionally, policy will surely place greater emphasis on the demand side, while also addressing societal and global challenges. Greater roles in technology diffusion and its co-ordination at regional and city levels will emerge, especially with enhanced efforts to channel the next production revolution in ways that redistribute manufacturing towards promoting local revitalisation and sustainability.

Overall, as production technologies transform, existing approaches to technology diffusion will need to be improved, and new diffusion models will be have to be fashioned, to facilitate efficient, effective and equitable deployment. New models are probably going to be more collaborative and open, with more diverse funding and creative approaches to building capacity and diffusing technology. These approaches can be adopted both by existing and new institutions. Innovation systems that have the foresight, flexibility, and drive to more rapidly enhance and refine their institutions for technology diffusion will be more likely to gain a competitive edge from the next production revolution. Systems that have weak or lagging institutions for diffusion could well be at a disadvantage, irrespective of their strengths in basic science.

However, challenges are evident for the diffusion of new production technologies and for the development of next-generation institutions for technology diffusion. Promising new technologies and models will come up against incumbent approaches deeply embedded in existing industrial facilities and ecosystems. For example, the fully integrated and automated factories proposed in the 1980s were not realised to the extent predicted due in part to the difficulty of incorporating existing supply chains and because of shortened product life cycles. Introducing new ways to integrate and diffuse technology can take time, patience and the ability to experiment. Yet many governments want visible results quickly, without risk. Additionally, while new production technologies are frequently promoted for their public value and their ability to address societal challenges, the funding and evaluation models under which many public technology diffusion institutions work lead to prioritising client counts and fee revenues rather than public values per se. There can be a focus on disseminating the latest advanced technology, when many enterprises and users lack absorptive capabilities for highly sophisticated methods. Such cases warrant pragmatic approaches to technology diffusion, coupled with long-term relationships that can build capabilities for more advanced strategies. Path dependencies in technology diffusion institutions themselves may also present roadblocks, leading to failure to upgrade expertise, services, and business models. Concerns over governmental accountability, combined with ongoing public austerity in many economies, could likewise mean that current institutions will be reluctant to risk change. This could slow the emergence of better institutions for technology diffusion.

Moreover, while effective institutions for technology diffusion are vital for deployment of the next revolution in production, especially for SMEs, these institutions cannot do everything. The scale, scope and quality of the diffusion of the next revolution in production also depend on national and regional innovation system frameworks. Elements involved here include provision for upgrading finance, infrastructure and education, including vocational training.

Policy recommendations

As discussed throughout this chapter, policy making needs to ensure the integration of technology diffusion and its institutions into the design and implementation of the next production revolution. While there is an inescapable emphasis on the exciting research advances and potential of the latest round of innovative new technologies, major economic and societal value will only be obtained if these technologies are responsibly designed and deployed in conjunction with users and other stakeholders, and if these technologies can be scaled up, diffused, and improved in use. Upgrading and reshaping the capabilities of technology diffusion institutions and integrating these institutions into next production revolution strategies are essential steps. Specific policy recommendations that would help to achieve these objectives are presented in Box 7.2.

Box 7.2. **Policy recommendations: Institutions for technology diffusion in the next production revolution**

- **Recognise that effective institutions are essential for the widespread deployment of the next production revolution.** Where such institutions exist, their role and mission must be integrated into next production revolution strategies. Where they are weak or non-existent, new institutional capabilities should be formed or created. The emergence of new institutions for technology diffusion should be nourished, experimentation and learning supported, and the development of relevant new skills and business models enhanced.
- **Refine and share effective practices for technology diffusion.** Institutions for technology diffusion should be encouraged to systematically review their service practices and approaches, to ensure that these practices are effective and customised for the communities they serve, to trial and scale up new approaches as needs evolve, and to exchange knowledge about practices. This requires policy attention to strategy, resourcing, operational support of management, personnel training, assessment and evaluation, and knowledge exchange.
- **Build collaborative understanding and joint action in the deployment of the next production revolution.** Next-generation production involves change in firms, but also necessitates engagement and co-ordination in value chains, sectors, and clusters. This is more than a technical mission. There is a need to engage firms, suppliers, users, and intermediary institutions in collaborative strategies to leverage the system and network attributes associated with the next production revolution. These collaborations will need to span regional, national, and international boundaries.
- **Ensure complementary innovation system framework policies, indirect measures, and demand-side incentives** to embed and amplify the effects of institutions for technology diffusion. It is vital to give attention to issues of policy mix and to organisational linkages to ensure that research and technology development are joined with diffusion, and that technology diffusion is integrated with related policies (including for finance, infrastructure, skills development, and procurement).
- **Address missions of sustainability and responsible research and innovation in the design and deployment of the next production revolution.** Attention to economic, societal, and environmental considerations has to be integrated into the policies of institutions for technology diffusion. This will involve engagement with clients, stakeholders and publics, as well as greater use of foresight and anticipatory approaches.

Box 7.2. **Policy recommendations: Institutions for technology diffusion in the next production revolution** *(cont.)*

- **Ensure the needs of SMEs are addressed in technology diffusion.** While institutions for technology diffusion work with many types of firms, particular attention is needed to help SMEs navigate the next production revolution. A foundational task is to build the absorptive and transformational capacities of SMEs to engage with, and benefit from, the next production revolution.
- **Address governmental failures in technology diffusion interventions.** Ensure that programmes working to upgrade existing firms (the majority of firms) are appropriately resourced, in addition to programmes that support advanced technology development and start-up enterprises. Develop management mechanisms to reform (or replace) technology diffusion institutions that are path-dependent and resistant to change. Ensure that government evaluation measures give more weight to longer-run capability development, rather than short-term incremental outcomes. Promote design/build/test approaches that can experiment with new models of technology diffusion, and encourage the incorporation of insights from these pilots into existing and new technology diffusion institutions.

As a corollary to the recommendations detailed above, with their focus on strengthening the roles and alignment of technology diffusion institutions in the transformation of manufacturing, there are also practices that policy makers should seek to avoid. Perhaps the first of these relates to the inclination to concentrate attention and resources on policies to back research breakthroughs and exciting laboratory technologies and to overlook, or at least poorly support, the industrial scale-up and diffusion of new technologies.

Furthermore, the diffusion of new technologies will not be accomplished only by strengthening technology transfer from universities, which tends to be focused on early-stage science. Similarly, it cannot be accomplished by turning to general business assistance programmes that provide tax breaks, loans, or conventional strategic planning services. The diffusion of technologies requires effective intermediary mechanisms of human interaction and the exchange of tacit knowledge. Moreover, while electronic communication and web-based resources are now indispensable aids, technology diffusion cannot be accomplished solely by posting assessment tools or briefing documents on the Internet: it requires experienced specialists with the knowledge and relational skills to understand problems and develop customised solutions.

Perhaps the most common pathway taken with diffusion of new technologies is to target them to likely early adopters. These adopters tend to be large multinationals, high-technology start-ups, and the small number of companies dedicated to the development of technologies. Policy attention should be placed not only on these early adopters, but also on the much larger number of existing SMEs. Not all SMEs can or will seek to modernise, but there are many SMEs that technology diffusion institutions can prompt and support to adopt new manufacturing technologies and approaches. A substantial part of the success of the next production revolution will depend on take-up by SMEs, and this will have leveraging effects on supply chains and regional clusters where SMEs predominate.

The stated rationale for policies to support institutions for technology diffusion is also important. In particular, such policies should not be pledged as programmes that can

restore lost manufacturing jobs or rapidly revive old industrial regions. Technology diffusion institutions can help firms today to adjust their business approaches and to adopt new technologies, products, and business strategies. This can help individual firms to stay in business and strengthen their abilities to offer good jobs (although new technologies may result in shifts in the profile of jobs and their tasks). It is likely that the major positive effects of technology diffusion institutions on upgrading the capabilities and performance of manufacturing communities to absorb next production revolution technologies will take time to materialise (five to ten years or more). Institutions and firms need time to build deep relationships and undertake collaborations. Indeed, the full outcomes of technology diffusion interactions, if they are substantial, will take significant efforts over many years to appear. This means that technology diffusion institutions need to be empowered and resourced to take longer-term perspectives. While it is desirable that services and programmes have flexibility, instability or short-term perspectives for the institutions themselves is not likely to support effective practice.

This chapter has argued that effective institutions for technology diffusion are essential for the widespread deployment of the next production revolution. The policy system tends to acknowledge this point at a high level, but then overlook technology diffusion in the subsequent allocation of attention and resources. It is important to redress this situation. Advantages will tend to flow to the companies and systems that are most effective in deploying the technologies and business models of the next production revolution. This chapter has also reinforced the need for complementary innovation system framework policies, indirect measures, and demand-side incentives to embed and leverage institutions for technology diffusion.

Building collaborative understanding and joint actions to deploy the next production revolution will also be an important task and challenge for institutions for technology diffusion. The systematic and networked nature of many aspects of the next production revolution demands a high level of co-operation among producers, users, and other actors. Technology diffusion institutions, which have often worked at an individual project level, now need to increasingly adopt strategies and actions that can work in multi-actor collaborations. These institutions need to span boundaries, be they at regional, national, or international levels, to access knowledge and forge new joint actions. Moreover, these institutions need to address missions of sustainability and responsible research and innovation in helping to deploy the next production revolution.

The adoption of new technologies and business models will probably be more prevalent and faster among larger companies, with an important role for disruptive start-up firms. However, a core mission of a system of technology diffusion is to ensure that existing SMEs are involved, that strategies and services are appropriate and affordable, and that more of these firms are encouraged to upgrade their absorptive and transformational capabilities.

There is a need to address governmental failures in technology diffusion interventions. These concern the attention and resources allocated to technology diffusion, the need to ensure that evaluation systems are appropriately focused on longer-term rather than short-run measures, and the importance of piloting creative and experimental approaches and then building insights from these efforts into existing and new institutions for technology diffusion.

Finally, it is also vital to undertake ongoing review and analysis of effective organisational designs and new models for technology diffusion under the evolving conditions of the next

production revolution. Yet, this involves more than undertaking assessment and evaluation, and sharing good practices, although these are all important. More fundamentally, there is a need for policy and management approaches that will stimulate technology diffusion institutions to upgrade their current methods and to trial promising new approaches, to embed innovative technologies and responsible methods into their own operations, and to enhance client and user absorptive capabilities.

Notes

1. It should be noted that this understanding of technology assumes that it is specifically or at least ultimately under human command. There are, however, long-running debates about technological control (see e.g. Winner, 1997), with increasing concerns more recently about autonomous technologies (Bostrom, 2014).
2. For further exposition of technology diffusion and related concepts of knowledge and innovation diffusion, see e.g. Geroski (2000), Everett (2003), and Stoneman and Battisti (2010).
3. Bayh-Dole Patent and Trademark Amendments Act of 1980, Pub. L. No. 96-517 (12 December 1980), 35 USC §§200-12.
4. Multiple factors are posited to understand how certain new technological designs become dominant, particularly where there is rivalry and competition, including appropriability regimes and complementary assets (see e.g. Teece, 1986). Nonetheless, as a rule, diffusion is essential to securing returns (especially spillovers and societal as well as private returns) to the prevailing technology.
5. The American Innovation and Competitiveness Act of 2017, Pub. L. 114-329 (6 January 2017).
6. 21st Century Nanotechnology Research and Development Act of 2003, Pub. L. 108-153 (3 December 2003), 15 USC 7501.
7. This section also draws on insights gained through interviews in Singapore by J. Youtie in March 2016.
8. For information on the KTN see *www.ktn-uk.co.uk/*.
9. Information available at *www.clusterplattform.de/SiteGlobals/CLUSTER/Forms/Suche/EN/Clustersearch_Form.html?* (accessed 12 January 2017).
10. Based on an interview with the senior counsel and director of BioBricks on 29 August 2016 and a review of the BioBricks website, retrieved from https://biobricks.org.
11. *www.manufacturingusa.com/* (accessed 12 January 2017).
12. *https://catapult.org.uk* (accessed 12 January 2017).
13. China has announced a national programme to upgrade manufacturing "Made in China 2025" (State Council, 2015). See also *http://english.gov.cn/2016special/madeinchina2025/* (accessed 12 January 2017).
14. Cell Therapy Catapult signs Memorandum of Understanding with Kanagawa Prefecture, Japan. *https://ct.catapult.org.uk/news-media/regulatory-news/cell-therapy-catapult-signs-memorandum-understanding-kanagawa-prefecture* (accessed 12 January 2017).
15. *https://es.catapult.org.uk/* (accessed 12 January 2017).
16. Broader definitions of sustainability encompass environmental, economic, and social sustainability. While this section focuses on environmental sustainability, topics related to economic and social sustainability are discussed under the heading of responsible research and innovation.
17. Engineering and Physical Sciences Research Council, Framework for Responsible Innovation, *www.epsrc.ac.uk/research/framework/* (accessed 12 January 2017).

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The Next Production Revolution
Implications for Governments and Business
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PART II

Chapter 8

Public acceptance and emerging production technologies

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Public acceptance of technology is a key factor in how innovation impacts society, and its consideration should therefore figure in policy making around the next production revolution. There is a persistent but misguided view that resistance to technology mostly stems from public ignorance about the true benefits of particular technologies or of innovation in general. Social science research shows that more important reasons for such resistance might be basic value conflicts, distributive concerns, and failures of trust in governing institutions such as regulatory authorities and technical advice bodies. In general, countries and innovators should take into account, to the greatest extent possible, social goals and concerns from the beginning of the development process. While it remains a challenge to realise this goal, best practices have emerged that can serve as a guide. These include funding social science and humanities in an integrated fashion with natural and physical science, using participatory forms of foresight and technology assessment to chart out desirable futures, and engaging stakeholders in communicative processes with clear linkages into policy. All of the above will help build trust and trustworthiness into innovation systems.

Introduction

Public acceptance of technology is a key component of innovation policy (OECD, 2016a) and should be an important consideration in policy making around the next production revolution. Strong public concerns can shape the direction, pace and diffusion of innovation, and even block its progress (Gupta, Fischer and Frewer, 2012). This is the case even where technical and economic feasibility have been demonstrated, the rationale for adoption appears sound, and large investments have been undertaken. In particular, emerging technologies have sometimes been frustrated because of social and ethical concerns (EC, 2013). At the same time, public resistance to technologies can give rise to regulations that promote trust and confidence, and steer innovation along acceptable pathways (Rodricks, 2006; Packer, 2008; Davis, 2014).

The consideration of public acceptance of the technologies of the next product revolution might be especially important today. The use and uptake of technology can be affected by the social and political contexts into which they are placed (Gupta, Fischer and Frewer, 2012). The development and adoption of production technologies are poised to affect labour markets in significant ways (The Economist, 2016), raising serious questions about public attitudes and acceptance of these new technologies. The stakes might be high: some see a number of the political events of 2016 as a popular reaction against prevailing manufacturing policies and the labour-market effects of technology.

Historically, public opposition has mounted in a number of fields of emerging technology, including nuclear power, genetically modified organisms (GMO), and other areas of biotechnology. In Europe, for example, negative public sentiment on GMOs has resulted in lower funding levels, high regulatory rejection rates, and lower levels of innovation than in other jurisdictions (Currall et al., 2006). Public investment can also become "stranded" (i.e. unable to be exploited). 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 around the world halted their broad diffusion (Winner, 1977).

This is not to say that publics are anti-technology. General attitudes of European citizens towards technology are regularly assessed by the Eurobarometer, a set of surveys conducted on behalf of the European Commission since 1973. While general public attitudes about emerging technologies are hard to gauge, there is evidence that societies are generally optimistic about technological development, although this is tempered by concerns. In a recent major survey in Europe, at least half of the respondents expected that, 15 years from now, science and technological development would have a positive impact on health and medical care (65%), education and skills (60%), transport and transport infrastructure (59%), energy supply (58%), protection of the environment (57%), the fight against climate change (54%) and quality of housing (50%) (EC, 2014a).

An assessment of public acceptance, however, must go beyond the measurement of attitudes and aim for a better understanding of the sources and drivers of acceptance. A first step is to understand that there are multiple "publics" in public acceptance. Recent

work on public acceptance in the context of renewable energy usefully illustrates the need to avoid a concept of public acceptance that is too thin. This work emphasises that acceptance depends not just on broad political acceptance by the public and key stakeholders, but also on acceptance by consumers and investors, and by communities in which new technologies are sited. Some academics term this the "triangle of acceptance" (Wüstenhagen, Wolsink and Bürer, 2007; Reith et al., 2013).

This chapter draws lessons from work in other science and research-intensive fields, such as health, while addressing concerns specific to a number of next product revolution technologies, particularly artificial intelligence (AI), industrial biotechnology and nanotechnology. Prior experience with the societal reception of emerging technology should help inform policy makers and other key actors as they push these technologies forward. There is a persistent but misguided view that resistance to technology mostly stems from public ignorance about the true benefits of particular technologies or of innovation in general. Social science research shows that basic value conflicts, distributive concerns, and failures of trust in governing institutions such as regulatory authorities and science advice bodies might be more important.

In general, countries and innovators should incorporate, to the greatest extent possible, social goals and concerns from the beginning of the development process. While it remains a challenge to realise this goal, best practices have emerged that can serve as a guide. These include funding social science and humanities in integrated co-streams with natural and physical science, using participatory forms of foresight and technology assessment to chart out desirable futures, and engaging stakeholders in communicative processes with clear linkages into policy. All of the above will help build trust and trustworthiness into innovation systems, which are critical factors in public acceptance.

Key technologies

Some of the technologies addressed in this report have already raised public concerns of various kinds, and are likely to continue to do so (EC, 2013). This section offers a brief review of public acceptance issues in biotechnology, nanotechnology, big data and AI. Some public concerns with emerging production technology have to do with risk, such as how new technologies might affect the health and safety of humans and the environment, and the idea that existing oversight is inadequate to anticipate potential harms. Other concerns have to do with issues of controlling life processes, or decision-making power over technology itself, such as through the control of intellectual property or market dominance. A major source of uncertainty about the path of these technologies lies in the fact that they are converging in unexpected ways, creating yet other new technologies. An example might be the convergence of information and communication technology (ICT) and biotechnology to produce synthetic biology approaches which form a platform for many other kinds of biological entities and tools.

Industrial biotechnology

The use of biotechnology on an industrial scale for fuels, chemicals, and other products isa likely element in the remaking of the production system (see Chapter 9). But, of course, biotechnology has also been the subject of persistent public conflicts over societal risks, especially in the context of GMOs and synthetic biology. In both developed and developing countries, GMOs have raised concerns around health and safety risks and the capacity to contain and reverse their release.

Negative perception has also centred on a linkage between biotechnology, seed patenting, and industrial concentration in the agro-food sector (Jasanoff, 2005). Such concerns have been resolved differently across countries, with some countries adopting genetically modified (GM) crops at a much slower rate than others. Starkly different regulatory approaches growing out of distinct public receptions of biotechnology have resulted in disruptions to international trade and have even triggered dispute settlement at the World Trade Organization (WTO) (Pollack and Shaffer 2009).

The biotechnology case suggests that government efforts to meet public concerns about technology by emphasising risk-assessment science may be only partially successful. In biotechnology, conflicts ostensibly about health and environmental risk reside, at least in part, in deeply held beliefs about the human-environment relationship, the ethics of human manipulation of "nature", and concerns about the corporate appropriation of biology (Jasanoff, 2005). However, because society may lack other outlets for deliberation on the moral implications of technology, the environmental and health safety risk becomes a primary locus of concern (Winickoff et al., 2005).

Box 8.1. **Gene editing in society**

With gene-editing techniques, especially those using the CRISPR-Cas9 system (named by the journal *Science* as the breakthrough discovery of 2015), scientists are now able to change a DNA sequence at precise locations on a chromosome. These techniques are successfully being applied to manipulate genomes for a wide range of applications. Gene editing will make the design and construction of organisms with desired traits easier and cheaper. It has been successfully used with organisms of commercial importance such as crop plants and farm animals, raising the possibility of developing new methods for the control of pests and diseases as well as improving the efficiency of plant and animal breeding. Recently, CRISPR has been used in the People's Republic of China to edit genomes of non-viable human embryos, and similar experiments have been approved in the United Kingdom (Callaway, 2016).

Certain scientific communities have taken a proactive approach to engaging in public discourse about CRISPR, which could be used in an array of settings including medicine, animal breeding, and environmental management. The technique has suddenly made potentially controversial applications of biotechnology more plausible, such as the precise editing of the human genome. 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 human 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 a summit of experts from around the world to discuss the scientific, ethical and governance issues associated with human gene-editing research (Reardon, 2015).

Bioproduction does not depend on agricultural feedstocks that are GM, but it certainly does involve sophisticated technical biochemical approaches to break down and reformulate organic material on a large scale. Governments still have to anticipate public concerns around recent biotechnological advances that make this possible. Recent developments in genetic engineering, particularly so-called "gene editing", have already

spurred public debate about the potential benefits and harms of that technology, particularly in the context of human germline engineering (Box 8.1). Synthetic biology, especially the development of novel sequences of De Novo DNA, has also provoked public controversy. Public discourse about these technologies, both within and across countries, is likely to have a large impact on industrial biotechnology (McNutt, 2015).

Nanotechnology

Engineering at the molecular scale through nanotechnology is anticipated to play an important role in the next product revolution (see Chapter 4). Beginning in the 1990s, governments and the private sector promoted nanotechnology as a key to future economic growth, and as an emerging tool to address societal problems. Industry, government, and academia invested significantly in nanotechnology and its commercialisation (Barben et al., 2007). Optimism about the potential of nanotechnologies to positively transform society spurred growth in nanotechnology innovation, but this enthusiasm co-existed alongside concern and protest. Prominent individuals such as Bill Joy and Prince Charles raised alarm bells, as did activist groups, including Greenpeace (Arnall, 2003) and the Erosion, Technology and Concentration Group (ETC Group, 2003). Joy (2000), for example, put forth a catastrophic "grey goo" scenario in *Wired* magazine, in which out-of-control self-propagating nanobots could obliterate life. Others were concerned with environmental hazards and unintended consequences (Tenner, 2001), shifts in privacy and security (MacDonald, 2004) and possibly greater economic inequality (Meridian Institute, 2005).

Such public concerns about nanotechnology intersected with existing antagonism towards biotechnology, evinced by the fact that the ETC Group (a civil society organisation focused on the socio-economic and ecological impacts of new technologies), which organised action in opposition to agricultural biotechnology, repeatedly called for a moratorium on some forms of nanotechnology research and development (R&D) because of concerns about environmental health and safety (Barben et al., 2007).

Informed by the experience with public opposition to GM foods in Europe, policy makers grew concerned that nanotechnology would draw broad public resistance. Policy makers in a number of countries took measures to promote broader societal considerations, integrating such considerations into nanotechnology R&D at early stages. Steps such as funding co-streams of social science research and various forms of public engagement were meant to ensure that science was responsive to societal needs and could more effectively support decision making.

In the United States, for example, and by contrast with earlier efforts, a piece of legislation passed in 2003 that sought to integrate social research and public input "upstream" in nanotechnology R&D policy. This focus on early or simultaneous integration of work on social concerns was similar to the approach adopted in the Human Genome Project's Ethical, Legal, and Social Implications Research Program in the United States. Similarly, the European Union, the Netherlands, Brazil and Colombia have established social science research on nanotechnologies and linked such work to decision making (Barben et al., 2007). A recent survey conducted by the OECD (2013) found that 11 of 25 countries surveyed have a specific policy with regard to the responsible development of nanotechnology, with several other countries having policies under development.

Unknowns about the health and environmental impacts of nanoparticles remain, which continues to raise concern among publics and regulators. Manufactured nanomaterials are found in more than 1 300 products currently on the market, including medical equipment, fabrics, fuel additives, cosmetics and plastics (US EPA, 2016). Regulatory approaches are still evolving, even as nanomaterials are entering waste streams. A recent OECD review of the literature on wastewater treatment – recycling, incineration, landfilling and waste water treatment – has found that significant knowledge gaps are associated with their final disposal (OECD, 2016a).

Big data

The next product revolution will be driven in part by digitalisation, and it is possible that large bodies of personal information will be collected and used in new production processes. Large-scale government programmes to collect and use big data for purposes of surveillance and national security have drawn major public concerns, but other areas have also become the subject of intense public debate. For example, health policy makers across the world are seeking to aggregate diverse health data from millions of people to enable comparative effectiveness research (CER) and help produce an innovative big-data architecture for research and discovery (Institute of Medicine, 2014). A central goal is to integrate population level and personal health data across the public and private sector to advance the evidence base for clinical care, monitor quality, and aid the discovery of biomarkers for the development of better diagnostics and drugs (Krumholz, 2014).

The challenges of integrating diverse health data sets and information architectures are technical, ethical and social. Collecting health data for research as it is generated in the clinic blurs the line between clinical care and research in new ways. Conducting predictive analysis to stratify populations raises concerns of justice, as certain populations may be included or excluded from desirable clinical trials or therapeutic interventions on that basis. Furthermore, obtaining traditional informed consent for the range and scale of potential uses is impossible (Faden, Beauchamp and Kass, 2014). 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). These social uncertainties are pressing many governments to develop partnerships and public dialogue with patients, health institutions, and other stakeholders in order to find acceptable solutions to questions of privacy, control and justice. OECD countries have recently addressed some of the challenges of managing health data in their recent *Recommendation of the Council on Health Data Governance* (OECD, 2017).

Artificial intelligence

AI technologies have the potential to transform society. But AI also raises a range of ethical, regulatory and social issues (United States, 2016). From automated assistants to driverless cars, AI stands poised for rapid growth, a view shared widely in Science ministries (G7, 2016). Some are optimistic about this innovation: advocates have argued that AI can both stimulate innovation and boost economic productivity, and perhaps improve the human condition more broadly. OECD research suggests that "big data used to feed machine-learning algorithms can boost industries including advertising, health care, utilities, logistics, transport, and public administration" (Bradbury, 2016). However, concerns about the risks, benefits, and ethical issues associated with these technologies appear to be growing. Professor Stephen Hawking has stated provocatively that "the development of full AI could

spell the end of the human race" (Cellan-Jones, 2014). Among the general public, concerns about the potential for AI to displace certain types of work are salient (Smith and Anderson, 2014), as are safety issues (Marks, 2016). A recent poll in Britain found that one in three people believe that the rise of AI is a threat to humanity (British Science Association, 2016).

Professor Dan Sarewitz, an expert in science policy, called for an informed, global public dialogue about AI and its potential impacts in a June 2015 article in *Nature* (Sarewitz, 2015). Still, robust mechanisms for addressing risks, benefits and ethical issues are not yet institutionalised (Calo, 2014). This is, in part, because AI is still being developed, and because wide and diverse applications make a comprehensive regulatory framework difficult. Moreover, some view policy interventions around AI with scepticism, arguing that it is too early for AI policy (McAfee, 2015), and that intervention could hamper technological development and the potential benefits to society (Brundage and Bryson, forthcoming). Others disagree, holding that regulation can itself enable innovation, and that AI already impacts our daily lives. To this end, the US White House Office of Science and Technology Policy, and European and British parliaments are conducting, or have conducted, public workshops on AI technology and policy. Some have called for national commissions on robotics (Calo, 2014). Importantly, many scholars have called for funding of early research into the human and social dimensions of AI technologies, integrated alongside technical research. Ensuring public acceptance of AI R&D will be critical to the future of this field.

Understanding public acceptance

Public acceptance or rejection of technology is a complex phenomenon that defies easy explanation. What follows is a discussion of social science literature and existing practices that help suggest approaches to how technology can best be brought into society in an acceptable fashion.

Risk perception and fallacy of the public deficit model

For some time, the leading idea on public resistance to technology was that it resulted from lack of information or education. This theory stems in part from classic studies that show a divergence between the risk assessments of lay people and those of experts (Slovic, 1987). These differences are patterned, revealing a bias towards certain technological characteristics. Technologies that are perceived to be irreversible, out of human control, and/or capable of catastrophic failure tend to raise the public perception of risk relative to expert appraisals. Similarly, if technologies are novel and less well-known, outside of human perception (e.g. nanoparticles invisible to the human eye), and delayed in their manifestation of harm, they also tend to be of higher public concern (Slovic, 1987). A number of next product revolution technologies have some of these characteristics. For example, biotechnology and nanotechnology have fast-evolving frontiers, novel physical properties, and their constructs are usually invisible to the human eye.

Studies of risk perception of this kind have led some governments to pursue education campaigns as a primary way of addressing public acceptance of technology. However, reviews of the correlation of education and technological acceptance are at best inconclusive. On controversial issues, there is no correlation at all and, in the words of one scholar "well-informed and less well-informed citizens are to be found on either side of the controversy" (Bauer, 2009). This finding comports with other social science work showing that where deeply held values and personal identities are at stake, science-based accounts are dismissed even by the most literate. It has been shown in one large study, for example,

that religious people with even the highest levels of science literacy tend to reject some core precepts of evolution (Kahan, 2015).

While education and information are important for shaping and framing public discourse on technology, public attitudes depend heavily on social and political contexts, and cultures of trust between citizens, regulatory agencies and firms. The following sections expand on this insight.

Trust in institutions

There is a close connection between public resistance to novel technologies and the disruption of trust in public regulatory authorities. In an important study of factors contributing to negative public opinion of GMOs in many parts of Europe, Gaskell et al. point out that "in an increasingly complex world, trust functions as a substitute for knowledge" (Gaskell et al., 1999). These authors argue that resistance to GMOs in Europe was closely tied to a lack of trust in regulatory procedures.

Box 8.2. **The HFEA's public consultation on animal DNA and embryonic research: Hybrids and mitochondrial replacement**

The United Kingdom's HFEA was established in 1990 to license and monitor in vitro fertilisation (IVF) and insemination clinics throughout the country, as well as institutions conducting embryonic research and the storage of gametes and embryos (Jasanoff, 2005). In 2007, HFEA launched a public consultation to explore the public's views on whether or not scientists should be allowed to create embryos containing animal DNA in embryo research (HFEA 2007; Blackburn-Starza, 2007). The programme, entitled Hybrids and Chimeras, involved a public consultation to facilitate engagement about the issue, and was supported by Sciencewise, a programme run by the Office of Science and Innovation which aims to assist policy makers in conducting public engagement activities.

The consultation ran from April to July of 2007, and involved a range of approaches to consultation. A public opinion poll sought to gather the views of a representative sample of the public in a general fashion. Public deliberations expanded upon these general findings and opened up new questions, focusing on the effect that deliberation and new information had on participants' views. A written consultation and a public meeting also took place. The results of the public consultation were analysed as evidence by the HFEA, which then decided that cytoplasmic hybrid research should be allowed to move forward, with caution and careful scrutiny (HFEA, 2007).

More recently, the HFEA gathered the public views and made a proposal to Parliament on whether to allow mitochondrial replacement in embryos intended for implantation. Parliament accepted the recommendation, with high public approval.

Other work on regulatory trust corroborates the above point. For example, in the late 1990s in the United Kingdom, public controversy erupted over how regulators poorly addressed uncertainties and contingencies in their management of bovine spongiform encephalopathy (BSE, or "mad cow disease"). Many commentators think that BSE crisis – especially the disruption of trust in the food safety oversight system – laid the groundwork for the broad resistance to GMO foods in the United Kingdom, even as regulators had deemed them safe (Pidgeon, Kasperson and Slovic, 2003). This case suggests that once trust is lost, it is hard to regain, even in other contexts.

This outcome is a stark contrast to the acceptance of reproductive medicine and technology in the United Kingdom, where a dedicated regulatory institution, the Human Fertilisation and Embryology Authority (HFEA), was established in 1990, prior to many controversial advances that have occurred. The HFEA has been successful at anticipating difficult oversight questions, and airing issues in public (Box 8.4). Resulting decisions regarding research and application in embryology research and reproductive medicine have garnered significant acceptance.

Technological hype – over-promotion of the benefits of technology – can undermine trust in governmental and scientific institutions. Emphasising novelty and near-term benefits can lead to disappointment and scepticism among publics (Rayner, 2004). For example, in the fields of stem cell research and clinical translation, there has been a sustained pattern of inflated predictions by scientific communities, funding agencies and the media (Kamenova and Caulfield, 2015). In California this has increased controversy, where a USD 3 billion dollar public initiative on stem cell research begun in 2004 has delivered scientific advances, but failed to deliver the tangible health benefits it advertised.

Values and uncertainties in risk governance and science advice

Key towards building trust in regulatory institutions is building trust in underlying analytic approaches and procedures, of which risk-benefit analysis claims the key position. Social scientists have learned lessons about where agencies can go wrong with respect to risk-based decision making and science advice.

Regulatory or technical advice bodies need to be transparent about how uncertainties are dealt with and what kinds of value-based assumptions are built into risk and benefit models. Controversies like the BSE outbreak mentioned above, and the Fukushima nuclear accident in Japan, indicate the need to better recognise, across expert communities and the public, how risk models necessarily have limitations and science-based regulatory decisions unavoidably carry value judgements (Pfotenhauer et al., 2012). Value judgements operate, for example, in the choice of which facts or kinds of expertise are relevant, in setting thresholds of sufficient evidence, in deciding how to cope with dissent, and in decisions to act in the face of uncertainty.

Box 8.3. **Value choices in science and technology advice: Examples and lessons learned**

Research in the field of science and technology (S&T) studies described the interplay of science and values in decisions at the intersection of science and policy. In particular, this research has demonstrated a demarcation process where science and society meet, sometimes known as "boundary work". Boundary work can be defined as a method of distinguishing policy-relevant knowledge from pseudo-science, politics or values. It is a demarcation process through which policy decisions regarding relevant evidence are placed on the "good science" side of the divide that separates objective knowledge from illegitimate, politicised or false science (Jasanoff, 1990).

Boundary work is considered necessary to accomplish at least two goals: to ensure that research responds to the needs of users (often policy makers) and that the credibility of science itself is maintained. One prominent example of boundary work involves attempts of governments to make a clear delineation between risk assessment and risk management, with social and economic factors entering only during the management stage.

Box 8.3. **Value choices in science and technology advice: Examples and lessons learned** *(cont.)*

This distinction also features prominently, for example, within international trade law and how it recognises valid versus invalid forms of plant health and safety regulation (Winickoff et al., 2005). Another involves the regulation of chemical carcinogens: establishing a cancer risk to humans based on direct evidence is often impossible, so regulatory decisions often rely on, for example, animal tests, which are interpreted with a great degree of uncertainty and disagreement, even within expert circles. As a result, the resolution of controversies about whether or not to regulate chemical compounds depends at least as much on the procedures and institutions used to resolve conflicts as the objective science itself (Jasanoff, 1990).

The existence of values-based disputes in science policy does not call into question the validity of technology assessments: rather, it argues for active boundary management by institutions tasked with governing technological risk, and suggests that appeals to scientific objectivity alone are unlikely to quell concern about the impacts of emerging technologies.

Recently, countries have acknowledged the importance of openness, integrity, transparency, and accountability in the establishment of trustworthy science advice (OECD, 2015). For example, in contrast to framing questions of science advice in exclusively technocratic terms, countries have begun to open up the process of science advice to make it more inclusive, and have been more scrupulous in characterising uncertainties and identifying questions that science alone cannot answer. In the United States, new ground was struck in this regard in the 1980s when acquired immune deficiency syndrome (AIDS) activists gained the necessary technical knowledge and political standing to participate in expert groups tasked to determine things like scientific criteria for inclusion in clinical trials (Epstein, 1996). Since then, patient groups "lay experts" in their sphere are often included on health policy task forces. Furthermore, policy questions are increasingly developed and framed in multi-stakeholder settings (OECD, 2015).

OECD (2015) described how a number of scientific advisory bodies have adopted new procedures and practices that might help to limit controversies over scientific advice and increase public trust in advisory systems. These procedures and practices include:

- **Clarified responsibilities.** If asked to address an issue, advisory bodies need to ensure that such a task is compatible with their mandate and expertise.
- **Increased transparency.** Potential or substantiated conflicts of interest have been responsible for much of the diminution of trust among citizens towards established structures and science-based policies. Experts are likely to have had previous contacts, and often contractual relationships, with some of the stakeholders involved in issues they have to examine. Better standardised definitions of "interests", and transparent rules to identify such interests, are therefore needed.
- **Stakeholder consultation.** Stakeholders are usually understood as people and organisations likely to be affected by decisions taken as a consequence of scientific advice, which can include those with economic interests as well as civil society groupings (e.g. NGOs, trade unions, patient organisations). To take into account the potential impact of their advice, an increasing number of advisory bodies are integrating some sort of consultation process with stakeholders alongside their traditional expert assessments.

- **Direct involvement of civil society.** A number of advisory bodies have gone one step further and included within their expert committees some representatives of civil society, including stakeholder groups (industry organisations, consumer associations) and lay persons. Although there are concerns that involvement of non-scientists in scientific advisory committees may dilute the quality of the science advice, it has been noted that, in many cases, these individuals have acquired a level of knowledge in the field sufficient to allow a good understanding of the issues at stake.
- **Public reporting and open communication.** To communicate scientific advice in a way that more fully engages society, science advisory bodies will need to make more effective use of social media.

Cross-national differences in regulatory style

There is no one-size-fits all approach for achieving a robust and trustworthy system of technical advice and regulatory oversight. Ultimately, societies have different modes of risk-based decision making and different ways of providing reasoning about S&T in public (Jasanoff, 2005). A significant body of social science comparing the treatment of risk-based decision making across national political systems demonstrates how differences in issue framing and science policy can lead to systematic transnational variations in the assessment of health, safety and environmental risk. Despite these differences, it is clear that across many countries transparency builds credibility as a general matter.

Laying the groundwork for public acceptance

Decades of work in the sociology of technology has shown how the path of technological development is not set in stone or predetermined, but can depend on human agency at the individual or policy level, as well as historical contingency (Bijker, Pinch and Hughes, 2012). It is true that the transformation of the production system will entail a large number of possible relevant research and technological choices made in unco-ordinated ways by people ranging from those who staff funding bodies to managers of institutions that support innovation, to entrepreneurs and workers. But it is also true that national investments and strategies will exert an influence on the direction of technological change. Can strategy and innovation policy address the issue of public acceptance from the beginning? This section reviews a number of strategies and mechanisms that could help create the conditions for technological acceptance where this is appropriate.

Foresight

Next product revolution-relevant technologies, from industrial biotechnology to 3D printing, appear poised to transform markets and, potentially, societies more broadly. But different futures are clearly possible. If an aim of policy is to increase public acceptance of next product revolution technologies, a reliable first step is to engage in foresight activities to identify trends in innovative fields and to co-ordinate, as far as possible, towards a range of socially optimal outcomes. While foresight exercises cannot predict the future, they can help to systematically and transparently identify and assess social, technological, economic, environmental and policy conditions that shape some aspect of the future (see Chapter 9). Good innovation policy can help steer technological trajectories towards agreed objectives, such as broad energy transitions or certain visions of medicines and human health. One benefit of engaging in foresight activities is process-related, including strengthening stakeholder networks and public engagement with technologies.

Examples of foresight processes might include the development of technology roadmaps, the use of bibliometric and patent data to consider technology futures, and expert elicitations. With regard to nanotechnology, for example, the United Kingdom's Economic and Social Research Council (ESRC) commissioned scenarios for converging technologies, to inform the council's research strategy (Barben et al., 2007). Mapping the potential futures of technological developments will be important to better understand social implications, and to identify possibilities for getting public buy-in during the innovation process. Some work to institutionalise this longer-term policy thinking is ongoing. For example, the German Federal Ministry for Economic Affairs and Energy and Federal Ministry of Education and Research created a co-ordinating body to bring together stakeholders to assess a long-term strategy for the future of industry.

Participatory technology assessment

Another mechanism to understand and enhance public acceptance of technology is to engage in processes of societal technology assessment. Having emerged in the 1960s, technology assessment has been increasingly adopted in many countries, and has evolved over time based on lessons learned. 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 view of broader social effects, health, and safety risk assessment. Some of these assessments are more broadly participatory and include procedures involving stakeholder and public input (Durant, 1999).

This broad set of societal technology assessment processes involves formal risk analysis but can also consider the longer-term social implications of technological adoption that may not easily be reduced to immediate health and safety risks. Questions to consider relate to the distribution of the possible benefits and costs; the consequences of intellectual property in the field; whether there are particular pathways of greatest social benefit; and sources of uncertainty in assessing the technology. These processes must also consider the potential benefits of innovation.

Generally speaking, there has been a shift from more expert-based forms of assessment to more participatory models (see below). Born out of controversies around technologies like nuclear energy, in the United States, technology assessment initially focused rather narrowly on the provision of objective, probabilistic knowledge about future trajectories of emerging technologies. Over time, there has been increased recognition that framing assumptions (e.g. problem definitions, scope and methodologies) shape the conclusions of technology assessment (Ely, van Zwanenberg and Stirling, 2011). In particular, an overemphasis on technical consequences can overshadow important issues associated with social, ethical and political impacts of technologies. For these reasons, countries began to shift to more inclusive, open and deliberative forms of technology assessment.

Some mechanisms of technology assessment involve formal public procedures that feed directly into innovation policy and governance decisions, particularly through the use of expert advisory bodies. One approach to technology assessment is the use of scientific academies or regulatory authorities to assess the most technical aspects of emerging technologies. Another is the establishment of public advisory bodies. Examples of these approaches include the Danish Board of Technology Foundation, the Nuffield Council on Bioethics in the United Kingdom, and presidential bioethics committees in the United States. Such groups might be charged with writing reports on particular technologies that gather evidence through research and public testimony and can inform public reasoning.

Public surveys and stakeholder interviews on emerging technologies might also be employed to assess technologies and gauge current opinion. Hearings which seek to collect input from various publics might also be used to inform regulatory agencies.

As mentioned above, recent efforts at technology assessment have taken a more participatory form. These approaches have variously been termed "constructive technology assessment" (Schot and Rip, 1996), "participatory technology assessment" (Guston and Sarewitz, 2002), and "real-time technology assessment", among others. These approaches emphasise the value of engaging citizens and stakeholders alongside expert analysis for effective technology appraisal. One reason for this shift is that, given that technology assessment is inherently value-laden, citizens should have a voice in these processes. In addition, there is a growing recognition that non-experts and other stakeholders possess knowledge relevant to technology assessment that would otherwise be missed. Toxicological risks are a good example. It is the users of potentially toxic substances in their places of work that are well positioned to provide knowledge e.g. of how workers might become exposed in particular workplaces, given normal habits. To give another obvious example, an assessment of the risks of pesticides would have to take into account the everyday practices of field workers, e.g. whether protective clothing is in fact routinely used.

More participatory modes of technology assessment recognise that the public is more likely to accept assessments of which they have been a part, and that the knowledge these assessments produce is likely to be more robust if diverse stakeholders are engaged. These approaches might include things like socio-technical mapping, which combines stakeholder analysis with plotting of recent technical innovations, early experimentation to identify and manage unanticipated impacts, greater dialogue between the public and innovators, public opinion polling, focus groups and scenario development, among others (Guston and Sarewitz, 2002).

Public engagement and public deliberation

In addition to formal technology assessment processes, engagement with stakeholders and publics more broadly on issues of science, technology, and innovation is increasingly recognised as an important feature of robust science and innovation policy. In their study of the acceptance of renewable energy technologies, Reith et al. (2013) identified three interventions that can enhance social acceptance of emerging technologies: greater information provided to the public (e.g. advertising, newspapers, websites, and excursions to sites), enhanced co-operation and participation (in decision processes and in financial arrangements), and public consultation and engagement (e.g. public meetings and dialogues). These approaches hold promise for the analysis and implementation of other emerging technologies (Reith et al., 2013).

Public engagements might be defined as "participatory processes through which members of diverse publics express their views, concerns, and recommendations about a techno-scientific issue. Such efforts frame publics not as passive recipients of expert knowledge, but as important actors shaping technologies and their trajectories" (Winickoff, Flegal and Asrat, 2015). Mechanisms of public engagement range from public consultation (e.g. surveys) to more dialogue-oriented public participation exercises (e.g. citizens' consultations and participatory technology assessment). Public engagement can help steer science and innovation towards socially desirable objectives, build a more scientifically literate, supportive and engaged citizenry, and broaden the range of perspectives considered in the development and conduct of research.

Box 8.4. **Scenario workshops for technology assessment**

The Parliaments and Civil Society in Technology Assessment (PACITA) Workshop: Scenario in Norway, Denmark, Austria, Bulgaria, Catalonia (Spain), Wallonia (Belgium), Czech Republic, Ireland, and Hungary.

As articulated in the Lund Declaration (a European declaration concluding that European research should be issue-oriented, and focused on meeting society's grand challenges), coping with ageing societies is considered a central challenge in Europe. Referred to as the "double demographic challenge," the ageing population's need for health care services is increasing as the size of the workforce declines. As a consequence, new technologies will be important for the provision of health care in the European Union.

To address the challenges and opportunities associated with a range of technologies (e.g. including smart houses, tracking devices and robotics), and to provide policy makers with a set of policy options, the European Union developed a project involving scenario workshops with stakeholders and publics, culminating in a policy report.

A stakeholder group was established with a variety of experts. Descriptions of technologies and an overview of potential future development were gathered, and a set of scenarios regarding the potential use of these technologies in an ageing society were produced. Scenario workshops were then organised in the countries listed above, aimed at assessing the similarities and differences across Europe with regard to the expectations and preferences on the technological challenges in question. Each workshop involved stakeholders, patients and users, technology developers and researchers, and decision makers at multiple levels. Feedback, general responses, issues and ideas were gathered during these deliberative workshops, recorded, and provided to policy makers.

The range of motivations for greater public engagement with S&T can usefully be considered in three categories: normative, instrumental, and substantive (Fiorino 1990; Stirling, 2007). From a normative perspective, the argument is that the governance of science and innovation without meaningful participation from interested stakeholders is contrary to democratic ideals. Citizens should have a say in whether and how S&T affect their lives. The instrumentalist argument is concerned with public acceptance of S&T: engaging the public upfront on questions of controversial S&T policy may stave off public outcry, and enhance trust between scientists and lay publics. Finally, substantive arguments state that public engagement, and in particular the incorporation of non-expert views, can enhance the quality and relevance of the knowledge produced, as well as the utility of technologies.

"Public engagement" in innovation policy often encompasses a wide range of instruments. A typology of public engagement mechanisms derived from Rowe (2005), with examples, can be found in Table 8.1. One form of engagement might be considered "communication," and encompasses instruments which convey information from policy makers (or other sponsors) to the public. In these efforts, information is unidirectional. Still, well-crafted communication can have significant implications for responsible innovation, in part because transparency can help foster public trust in science advice. Examples of different forms of relevant communication include, for example, making strategic research plans accessible to the public, either in hard copy or online, or "open science", defined as "an approach to research based on greater access to public research data, enabled by ICT tools and platforms, and broader collaboration in science, including the participation of non-scientists, and finally, the use of alternative copyright tools for diffusing research results" (OECD, 2016b).

Table 8.1. **Typology of public engagement mechanisms and some country examples**

Key policy features		Key policy instruments	Some country examples
Communication	Online notice	Publishing research plans/ regulatory actions on website accessible to public	Lithuania's public e-platforms; Poland's Public Information Bulletin
	Open science	Open access to academic research	South Africa's Scientific Electronic Library Online; Turkey's Ankara Statement on Open Access and National Open Science Committee
Consultation	Public input on agenda setting	Surveys, online feedback, bottom-up sourcing, etc.	Colombia's Ideas for Change Program; Turkey's Technology Roadmaps; Netherlands' National Research Agenda; Argentina's Argentina Innovadora 2020; The Great New Zealand Science Project
Participation	Anticipatory governance	Foresight activities regarding technology assessment	Czech Republic's PACITA; Germany's BMBF Foresight Process
	Dialogue for identifying research priorities	Workshops with publics to identify key societal questions	Germany's dialogue on future technologies; Denmark's INNO+ Catalogue
	Citizen science		Austrian Centre for Citizen Science

Another form of engagement is "public consultation", in which policy makers (or other sponsors) initiate the collection of input from the public. Public consultation does not generally entail formal dialogue between publics and policy makers. Nevertheless, information elicited by policy makers from the public can help guide socially responsive innovation activities. Examples of public consultation include formal requests for public input regarding research priorities, the conduct of surveys regarding public views on e.g. S&T.

Unlike the aforementioned forms of engagement, "public participation" entails a formal dialogue between policy makers and publics. Of central importance in participatory exercises is the act of deliberation. Information is exchanged across experts and lay publics, which can facilitate mutual learning and even changes in opinions of both policy makers and public participants. One example of public participation includes participatory technology assessment methods.

The trend towards greater adoption of public engagement mechanisms in innovation policy suggests that they are perceived by countries as beneficial. But some challenges exist to their effective implementation. First, constructing representative publics through such exercises can prove challenging. Some public engagement processes are only viewed as legitimate for those publics directly engaged in them. This has been termed a "fundamental problem of scale" (Lövbrand et al., 2015; Stilgoe, Lock and Wilsdon, 2014) and points to the need to consider engagement exercises as only one element of more responsible innovation policy. Another challenge relates to making STI policy responsive to the outputs of public engagement efforts. There is some risk that weak public engagement does not facilitate true deliberation, and instead serves to legitimate existing policies. Furthermore, public engagement is most likely to be impactful when technologies are further "upstream," or before they are locked in (Collingridge, 1980). This means that, while especially effective in cases of emerging technologies, public engagement can be more challenging for technologies that are already deeply entrenched.

Sweden's nuclear waste programme provides a good example of a deliberative process that successfully bridged expert and lay divides to produce a societally acceptable decision on the future of a technology. In the 2000s, in response to social concerns about the siting of nuclear waste, Swedish officials conducted and presented a "safety case" as a primary tool in

developing a public deliberation on the topic, and the process resulted in a publicly approved, licensed facility (Long and Scott, 2013; European Nuclear Society, 2009). The case materials conveyed technical arguments in lay language about why the proposed repository was thought to be safe. It clearly described what was thought to be the quality of the information used in the case. It also described plans for what would be done to improve understanding, the expected outcome of these efforts, and how previous efforts to improve understanding had performed. At a follow-up, the results of recent experiments were compared with previously predicted results. Over time, the transparency of this process enabled everyone to perceive an increasingly accurate understanding of its performance (Long and Scott, 2013).

Experience in the field of health innovation shows how patients, research participants, and lay publics – if consulted in the course of R&D – can foster innovation and steer innovation towards real needs. For example, in the arena of rare diseases, disease advocacy organisations have organised their own biobanks, recruited researchers to work on their diseases, co-invented tools for interventions, and served as key advisers in shaping the regimes of research ethics for clinical trials.

Integrating ethical, legal and social issues upstream

Potential social concerns and the issue of public acceptance should not be left to the very end of the technology development process. It is increasingly recognised that it is important to integrate the consideration of such issues through the activities of research funding decisions, the practice of science, technology development and commercialisation. How can this be done?

The first generation of approaches to integrating broader social concerns in the development and assessment of technology involved attention to ethical, legal, and social issues (ELSI). Since the Human Genome Project (HGP) in the early 1990s, science funders in many OECD countries have sought to implement ELSI. The planners of the HGP recognised that the information gained from 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 ethical, legal and social implications of research. In the realm of nanotechnology, 2.4% of the National Nanotechnology Initiative in the United States was dedicated for ELSI research, and in the Netherlands 25% of the national research programme on nanotechnology was dedicated to risk research and technology assessment (OECD, 2013). Since this pioneering approach, efforts have been made to mainstream social science and humanities work into funding streams, and this is taking root in many OECD countries.

New mechanisms seek to integrate social considerations not at the end of technology pipelines, but in the course of technology development, to support innovation rather than constrain it. Examples of such comprehensive approaches include the US National Nanotechnology Initiative and the Horizon 2020 programme at the European Commission (Box 8.5).

Growing out of aforementioned efforts, from ELSI to technology assessment and public deliberation, RRI has gained traction in the EU policy context. RRI combines elements of upstream assessment, public engagement, open access, gender equality, science education, ethics, and governance. RRI aims to open up issues related to S&T innovation, anticipate their consequences, and involve society in deliberating over how S&T can be responsive to societal goals and concerns. RRI, as a concept and set of tools, has evolved substantially since its introduction into EU policy discourse in 2011.

Box 8.5. **Anticipatory governance**

The US National Nanotechnology Initiative (NNI) began in 2003 and co-ordinates over USD 1 billion of research per year. The NNI emphasises the need for commercialisation for competitiveness on one hand, and the need to better understand societal impacts on the other. The NNI established two centres to investigate "nanotechnology in society." These centres have developed an "anticipatory governance" approach that aims to build societal capacity to engage with innovations in nanotechnology. Anticipatory governance has at least three components and is intended to achieve:

1. Consideration of human values in deliberations about technology, often through the direct engagement of stakeholders and the lay public. The Nanoscale Informal Science Education (NISE) Network in the United States has featured public engagement as a major theme.
2. Scenario development and foresight to help develop understanding of the social dimensions of scientific and technical change. Illustrative programmes include the Scenarios of Converging Technologies programme at the University of Oxford, and the open-source scenario development initiative under the NanoFutures project at the Centres on Nanotechnology and Society.
3. Integration of engagement and foresight with scientific and technical work to increase the ability of natural scientists to understand the societal aspects of their own work, and to inform the perspectives of social scientists on cutting-edge technology (Guston, 2008).

Box 8.6. **Understandings of RRI**

Definitions of RRI vary across government and academic communities, and treat RRI variously as an approach to governance, a policy framework, and a process. Salient definitions include:

- An approach that anticipates and assesses potential implications and societal expectations with regard to research and innovation, with the aim to foster the design of inclusive and sustainable research and innovation. It implies that societal actors (e.g. researchers, citizens, policy makers, businesses and third sector organisations) work together during the whole research and innovation process in order to better align both the process and its outcomes with the values, needs and expectations of society (EC, 2017).
- "A science policy framework that attempts to import broad social values into technological innovation processes while supporting institutional decision making under conditions of uncertainty and ambiguity. In this respect, RRI refocuses technological governance from standard debates on risks to discussions about the ethical stewardship of innovation" (Schroeder and Ladikas, 2015).
- "A transparent, interactive process by which societal actors and innovators become mutually responsive to each other with a view to the (ethical) acceptability, sustainability and social desirability of the innovation process and its marketable products (in order to allow a proper embedding and technological advances in our society)" (Schomberg, 2013).

One thrust of RRI is the desire "to connect the practice of research and innovation in the present to the futures that it promises and helps bring about" (Owen, Bessant and Heintz, 2013). "Prediction is impossible," as one academic has stated, "but anticipation of possible, plural futures is vital" (Stilgoe, Bessant and Heintz, 2013).

RRI is not regarded as an approach to implement measures of liability, accountability, stronger regulation, or another form of ethical review. Instead, stakeholders are encouraged to discuss collectively avenues for advancing societal goals through technology, considering the full range of moral, ethical, legal and social implications of research and innovation (Owen et al., 2013). As part of the European Union's Horizon 2020 programme, RRI forms a key action of the "science with and for society" objective of the European Commission. Governments should ensure that policies, regulatory frameworks and funding initiatives embody the principles of RRI in order to deliver on the promise of smart, inclusive and sustainable solutions to the social challenges discussed under the so-called Rome Declaration (EC, 2014b).

Conclusion

The current transformation of the production system will entail a large number of research and technological choices across value chains and sectors. But national investments and strategies can and will exert a profound influence on the direction of technological change. There are important technological precedents for policy makers, industry, and society to consider in the context of public acceptance. The biotechnology case suggests that government efforts to meet public concerns about next product revolution technologies by focusing on immediate physical risks rather than longer-term social concerns could run into problems. In the case of nanotechnology, science funders invested in social science and social outreach through the creation of Centres on Nanotechnology and Society, and little public resistance has developed. Big data and AI are areas in which societal dialogue has begun in earnest, but in which few institutionalised fora exist for communication and learning.

Social science literature on public acceptance carries a number of key points for policy makers:

- **Public understanding of science.** While education and information are important for shaping and framing public discourse on technology, public attitudes depend heavily on social and political contexts, and cultures of trust between citizens, regulatory agencies and firms.
- **Trust.** There is a close connection between public resistance to novel technologies and the disruption of trust in public regulatory authorities. The logics, value choices, and uncertainties underlying analytic approaches such as risk-benefit analysis should be transparent. Hype around near and long-term benefits can ultimately undermine trust in governmental, the private sector and scientific institutions.
- **Science advice.** Trust begins with the trustworthiness of regulatory and expert advice bodies, and they should be characterised by openness, integrity, transparency, and accountability. There is no single and one-size-fits all approach for achieving a robust and trustworthy system of technical advice and regulatory oversight. Ultimately, societies must draw on the best of their own institutional traditions for public reasoning on technical issues.

A number of mechanisms and good practices exist for promoting the societal capacity for coping with and engaging well with technological choices:

- **Anticipation.** A reliable first step is to engage in anticipatory activities – such as foresight – to identify trends in innovative fields, imagine possible futures, and to co-ordinate social actors, as far as possible, towards a range of socially optimal outcomes. While

foresight exercises cannot predict the future, they can help to systematically and transparently identify and assess a range of conditions shaping the future.

- **Participatory technology assessment.** Different forms of participatory technology assessment are now carried out by a mix of actors, including national ethics committees and other government bodies tasked with taking a view of broader social effects, and health and safety risk assessment. Questions to consider should relate to: the distribution of the possible benefits and costs associated with a particular technology; the consequences of intellectual property in the field; whether there are particular pathways of greatest social benefit; and sources of uncertainty in assessing the technology. These processes must also consider the potential benefits of innovation.
- **Public engagement.** Public engagement can help steer science and innovation towards socially desirable objectives, create a more scientifically literate, supportive and engaged citizenry, and broaden the range of perspectives considered in the development and conduct of research. Public engagement is most likely to be impactful when technologies are further "upstream," or before they are locked in, and good practices have been developing.
- **Integrating ethical, legal and social issues in upstream R&D.** It is important to integrate the consideration of such issues through the activities of research funding decisions, and the practice of science, technology development and commercialisation. Approaches such as "anticipatory governance" and "RRI" provide possible frameworks for doing so, but mechanisms require further development and experimentation.

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The Next Production Revolution
Implications for Governments and Business
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PART II

Chapter 9

The role of foresight in shaping the next production revolution

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Foresight can be a highly useful tool to address the opportunities and challenges triggered by the next production revolution. As shown by the various country cases considered in this chapter, foresight facilitates debate and systemic thinking about multiple futures and helps to shape the future through processes of participation and engagement. Given its participatory nature, key actors are mobilised to form shared views about the future, negotiate their future stakes and interests, and agree on actions aligned with their shared vision. The next production revolution requires quick and proactive policy making, as well as better orchestration across different policy domains. Foresight can assist policy makers by providing foundations for robust policies, reframing policy issues, and translating long-term concerns into aligned policy priorities. Furthermore, policy implementation is likely to be faster and more effective when key stakeholders are involved early on in shaping the policies. Foresight benefits, however, are far from being automatic: the chapter considers eight factors critical to achieving the benefits. Ultimately, beyond just foresight recommendations, policy makers must be prepared to act.

Introduction

Day-to-day decisions, taken by policy makers or the leaders of private or societal organisations, guided by long-term strategic thinking tend to lead to more targeted outcomes than ad hoc decisions. While there are many approaches to strategic thinking, those that rely on foresight tend to be more robust because they cover a broad spectrum of possible long-term futures as inputs to strategy development. This applies a fortiori to decisions that seek to position a country, a region or a firm amidst the turbulence caused by the next production revolution.

Of various types of prospective analysis, this chapter focuses on foresight because this is a particularly relevant policy approach to address the opportunities and challenges triggered by the next production revolution: besides facilitating debate and systemic thinking about possible futures, foresight also helps to shape the future. A well-designed and conducted foresight process identifies and assesses in a systematic and transparent way those societal, technological, economic, environmental and policy factors and trends that are likely to affect competitiveness, wealth creation and quality of life. Such analysis can help policy makers define issues and design policies. Foresight can help turn long-term concerns into urgent policy priorities. At the same time, foresight can raise awareness and understanding of such factors among stakeholders, mobilising them to act and preparing the ground for complementary actions and strategies. In this way, foresight can contribute to the emergence of more coherent expectations and strategies, making policy implementation more effective. By exploring multiple scenarios for the future (as opposed to a single future) and by bringing together major stakeholders with diverse backgrounds, foresight can help decision makers cope with an uncertain future and provide foundations for more robust policy making.

To reap the benefits of foresight, policy needs to be receptive to the processes that foresight requires and the policy proposals it yields. Ideally, foresight should be institutionalised, with regular rounds of foresight supported by continuous horizon-scanning. A fundamental condition for achieving impact is to have a committed policy client. Foresight should be embedded in the decision-making system. A suitable choice of timing, relevance to major policy issues, and co-ordination with other policy initiatives are all critical. It is also crucial to find an organisational set-up that eases the inherent contradiction between the need for foresight work to be close to decision-making processes (to achieve impact), and the need to maintain intellectual autonomy (to generate original ideas and out-of-the-box thinking). Any solution to this perennial tension can only be context-specific.

The next section briefly reviews the most important types of prospective analysis and their policy relevance in the context of the next production revolution. The potential benefits of foresight and its roles in shaping policies are then discussed, again in comparison with other types of forward-looking analysis. Before summarising the main policy and organisational lessons, several factors are highlighted to help policy makers maximise the benefits of foresight.

Foresight and its policy relevance

Locating foresight among prospective analytical tools

Prospective analyses can take various forms and pursue different purposes. The best-known forms include forecasting, key technologies exercises, foresight, strategic planning in the private sector and indicative national planning. This chapter focuses on foresight. But to better understand foresight's policy relevance – what can and cannot be expected from foresight – it is worth briefly juxtaposing foresight with other types of prospective analysis, in particular forecasting and expert-based (non-participatory) prospective analysis. First, two fundamentally different systematic approaches to the future are considered: forecasting and foresight.[1] Forecasters assume that the future is essentially determined by fairly stable structural and institutional settings, the main features of which can be called driving forces. The main task is thus to identify these driving forces, devise a reliable quantitative model, collect the relevant data and run simulations to generate future extrapolations at given points in time. Experts need to be involved in developing these future extrapolations, which may differ from each other quantitatively, but not structurally (i.e. the same variables are used throughout, even if their values change from forecast to forecast). Forecasting can be used either for pure academic exercises or as a decision-preparatory tool in the public or private sector.

Foresight processes, in contrast, assume that the future can be shaped by deliberate present-day actions: at least some unfavourable trends can be altered (redirected, slowed down, or stopped altogether) to some extent and new, desirable ones can be set in motion as a result of private and public actions. Foresight, therefore, explores different possible futures. In uncertain times, thinking in terms of multiple possible futures is a necessary precondition for devising strategies to cope with unexpected developments.

To realise foresight's potential to shape the future, important stakeholders need to be involved not only to identify, but also to assess, the major (current, emerging and future) trends, consider feasible futures, and select the most favourable one. In this way, values and interests play a decisive role in foresight processes, and thus it is crucial to make the entire process inclusive and transparent. With the help of participatory methods, foresight can incorporate different perspectives when exploring possible futures and bring to the fore a range of relevant influences on, and impacts from, the issues in question. The process itself can have systemic impacts: due to intense dialogue, existing networks of major actors are likely to be strengthened, new ones created, and a future-oriented way of thinking reinforced. The novel, participatory methods also reshape the overall decision-making culture in the affected policy domain.

Furthermore, most foresight activities aim at achieving a common understanding of what a desirable future might be. Such visions and – associated with them – more operational roadmaps, can be powerful instruments to assemble different key players around a shared agenda. The main benefit of such visions, roadmaps and strategic agendas is that they help reduce uncertainty about the ambitions of partners and competitors, and thus assist long-term decision making. Moreover, once participants arrive at a shared vision, they can expect that most of their fellow participants will take steps to achieve that chosen future state, and thus align their future actions to the jointly identified favourable future.

Foresight needs to be clearly distinguished from the strategies it is supposed to feed. In the context of the next production revolution, the German Industry 4.0 (Plattform Industrie 4.0) initiative may serve as an example of a strategy inspired at least partly by prior foresight activities in Germany.

The next production revolution is likely to trigger complex changes, given the interactions of new technologies (such as 3D printing and scanning, the Internet of Things, machine-to-machine (M2M) and person-to-machine (P2M) communications and interactions, and advanced robotics); new materials (in particular bio- and nano-based materials); new processes (e.g. data-driven production, artificial intelligence and synthetic biology); and new business models (exploiting mass customisation, sharing and the platform economy) (OECD, 2016a, 2016b). These changes would affect research, technological development and innovation activities (direction of search, allocation of funds, commercialisation, ethical concerns); the labour market (via job creation and job destruction); income distribution and well-being; skill requirements (and thus formal training via the education system, retraining, life-long learning); and, several fields of regulation (e.g. intellectual property rights [IPRs], privacy, security and safety investment). Furthermore, digitalisation can be a major enabler of the circular economy (e.g. via mass customisation, smart logistics, smart cities, and smart homes). The policy implications of the next production revolution are so wide-ranging that it would be difficult to mention a major policy domain that will be untouched by the sorts of sweeping changes noted above.

The need for policy orchestration is, therefore, rather strong. Foresight would assist policy makers in dealing with these complex changes and challenges in three ways.[2] First, it would facilitate a systemic approach, consider multiple futures and draw on the diverse knowledge and experience of participants. Furthermore, a strong sense of ownership among participants could work to keep up the momentum of orchestrated policy design and implementation. Second, the next production revolution is likely to increase uncertainty. Yet, a shared vision, developed – and thus "owned" – by the major stakeholders participating in a foresight process, can reduce uncertainty. Third, the next production revolution is also likely to induce systemic changes, e.g. in the form of emerging innovation ecosystems or radically overhauled national, sectoral or regional innovation systems. A transformative foresight process, aimed at considering and assisting these systemic changes, can contribute to reshaping the prevailing power structures (which might constrain the desired changes) and rejuvenating policy rationales, the overall decision-making culture and methods, and thus the efficacy and efficiency of policies.

Both forecasting exercises and foresight processes rely on a rich arsenal of quantitative and qualitative methods, including simulation, extrapolation, Delphi surveys, horizon-scanning, PESTLE (political, economic, social [socio-cultural], technological, legal and environmental) and SWOT (strengths, weaknesses, opportunities and threats) analysis, as well as scenario development (Box 9.1). Several of these methods, such as simulation, horizon-scanning, SWOT and scenario analysis, are widely used as part of day-to-day decision-preparatory processes. A given foresight process relies on a bespoke set of tools and methods to identify and assess in a systematic and transparent way those societal, technological, economic, environmental and policy factors and trends that are likely to affect competitiveness, wealth creation and quality of life.

Depending on the methodological approach taken, foresight exercises can generate a variety of "products", including thematic reports by panels, lists of priorities, policy recommendations, and roadmaps. These may be generated as intermediary products during the process or as end products. They are often the most visible outputs of a foresight exercise and may be extensively used in policy planning, including by those not directly involved in the foresight process.

Box 9.1. **Selected methods for prospective analyses**

STEEPV (social, technological, economic, environmental, political, and value-driven) factors and trends, together with **PESTLE** analysis, provide a simple framework to identify major driving forces and trends. **SWOT** analysis is used to identify and categorise significant internal (strengths and weaknesses) and external (opportunities and threats) factors faced by an organisation, a city, a region, a country or a world region.

Horizon-scanning is aimed at detecting early signs of potentially important developments. These can be weak (or early) signals, trends, wild cards or other developments, persistent problems, risks and threats, including matters at the margins of current thinking that challenge past assumptions. Horizon scanning can be comprehensive or a limited search for information in a specific field defined by the objectives of a given task. It seeks to determine what is likely to be constant, what may change and what is constantly changing in the chosen time horizon (short-, medium- or long-term).

Trend extrapolation first identifies a trend that is apparent over time and then projects it forward based on data concerning rates of change. In shorter-term forecasts a linear or exponential curve (e.g. economic growth or diffusion of a technology) is extended. To use extrapolation in the longer term, there should be confidence that the underlying driving forces would persist.

Simulation creates and experiments with a computerised mathematical model imitating the behaviour of a real-world process or system over time. Simulation is used to describe and analyse the behaviour of a system by asking "what if?" questions about the real system. In this way, it can assist in the design of real systems.

A **Delphi** survey is an expert survey conducted in two or more "rounds". In the second and later rounds of the survey, results of the previous round are made available for the respondents to consider. From the second round on, therefore, the respondents are aware of their colleagues' opinions when they give their answers. Giving this type of feedback differentiates Delphi from ordinary opinion surveys. The underlying idea is that the respondents can learn from the views of others, without being unduly influenced by those who are most forceful in meetings, or who have the highest prestige. Ideally, significant dissenters from an evolving consensus are required to explain the reasons for their views, and this would serve as useful intelligence for others.

A possible set of future situations can be described and discussed at different lengths and for somewhat different purposes in "visions", "futures" and "fully fledged scenarios":

A **vision** is a rather short description (a single paragraph) of a desired future that aims to unite and mobilise people to accomplish a particular vision.

A **future** is a detailed description of a particular situation (outcome of important developments with its major features and interrelationships) in the future. Compared to a vision, it is more detailed, analytical, and neutral. Put succinctly, a vision is normative, while a future is descriptive (a tool for exploration).

A **fully fledged scenario** (or path scenario) contains a future, as well as the path leading to that future, that is, the major decisions and steps to be taken to reach that particular future.

To be effective, visions, futures and fully fledged scenarios must be plausible, consistent and offer insights into the future. They should be structurally different, i.e. they should not be so close to one another that they become simply variations of a base case. They can draw on many different sources and methods, potentially including all those listed above, as well as brainstorming and specifically designed scenario-building workshops.

Box 9.1. **Selected methods for prospective analyses** *(cont.)*

In contrast to simulation, futures and fully fledged scenarios can explore relationships and trends for which little or no numerical data are available, including shocks and discontinuities; they can more easily incorporate motivations, values, and behaviour; and they can create images that capture the imagination of those for whom they are intended. They can help decision makers think about the future in a systematic way by considering a range of plausible futures. These tools also help stimulate creativity and break away from the conventional obsession with present and short-term problems.

A **critical (key) technologies study** aims to identify short-term (three to ten years) research and development policy priorities. Its decisive feature is the set of criteria against which the "criticality" (the importance) of particular technologies are assessed. It is based on interviews with experts and in some cases on a benchmarking analysis with a selected country or region.

Sources and further readings: Cuhls, K. et al. (2015), "Models of horizon-scanning: How to integrate horizon-scanning into European research and innovation policies", *www.isi.fraunhofer.de/isi-wAssets/docs/v/de/publikationen/CU_ERL_PW_Models-of-Horizon-Scanning.pdf*; Gavigan, J. et al. (2001), "A practical guide to regional foresight".

Foresight is practised in many domains and at sectoral, local, regional, national and international levels. Several foresight exercises have focused solely on manufacturing and production, including "Making Value for America: Embracing the Future of Manufacturing, Technology, and Work" (Donofrio and Whitefoot, 2015), "The Future of Manufacturing: A new era of opportunity and challenge for the UK" (Foresight, 2013), "The Future of Manufacturing in Europe 2015-2020: The challenge for sustainability (FutMan)" (see Geyer et al., 2003) and "Manufacturing Visions – integrating diverse perspectives into pan-European foresight (ManVis)" (Arilla et al., 2005). Other foresight exercises have covered numerous fields, including manufacturing, and are typically wide-ranging national efforts. They include the various rounds of Chinese, Finnish, German, Japanese, Korean, Russian and UK national foresight programmes, as well as one-off national foresight programmes, e.g. in Greece, Hungary, Italy, Poland, Portugal, Slovakia, Slovenia, and South Africa.[3] The large – and increasing – number of foresight programmes suggests that foresight can be a useful policy tool in rather dissimilar innovation systems.

At the same time, continuous horizon-scanning activities are tightly embedded in government organisations in several countries. The particularly relevant examples are the UK Horizon-Scanning Programme, the Centre for Strategic Futures in Singapore, and Policy Horizons Canada, which has been conducting several metascan projects in recent years.

Four archetypes of prospective analysis addressing next production revolution issues

Prospective analyses can take many different forms, varying in their specific aims, thematic coverage, geographic scope, focus, methods and time horizons. They also vary in their breadth of thematic coverage (a focus on science and technology [S&T] issues versus a broader focus on innovation and production systems) and their breadth of participation (confined to topic experts versus broader participation). Combining these distinctions, four different archetypes of prospective analysis can be identified (Table 9.1). These four archetypes[4] are explained in more detail below and illustrated by short descriptions of actual cases.

Table 9.1. **Four archetypes of prospective analyses, with selected examples**

		Breadth of thematic coverage ➔	
		S&T focus	Focus on innovation and production systems
Breadth of participation ➔	Expert-based	Productive Nanosystems: A Technology Roadmap, (US, 2007) Korean Delphi surveys (since 1994, the most recent one conducted in 2015–16) ManVis (EU, 2003-06)	Making Value for America: Embracing the Future of Manufacturing, Technology, and Work (US, 2015) FutMan (EU, 2001-03)
	Participatory	Exploiting the Electromagnetic Spectrum, (UK Foresight, 2004) Nanotechnology for Podlaskie 2020 (Poland, 2009-13)	FinnSight 2015 (Finland, 2006) BMBF Foresight (Germany, 2007-09, 2012-14) Advanced Manufacturing Partnership (US, since 2011) The Future of Manufacturing: A new era of opportunity and challenge for the UK (2013) The more recent Japanese foresight programmes

Source: Authors' analysis.

Varying breadth of participation: Expert-based projects versus participatory processes

As highlighted above, foresight is a participatory process, but some types of prospective analysis can be conducted by small(er) expert teams, too. These projects can consider either a single future or multiple futures. In contrast to foresight processes, these are likely to be shorter, and thus cheaper projects, and can have more direct, more visible, and more easily identifiable impacts on certain policy decisions. Key technologies exercises fall into this category and have been conducted, for example, in the Czech Republic (Klusacek, 2004), France – where the Technologies Clés exercises are carried out every five years – and the United States. Yet, these types of project are unlikely to result in a shared vision, reduced uncertainties, and systemic impacts. In particular, it is unlikely that the overall decision-making culture would be altered. Neither would the views of citizens and non-governmental organisations (NGOs) enrich policy dialogue when this tool is used.

Varying breadth of thematic coverage: Focus on S&T developments versus focus on innovation and production systems

A given prospective analysis can aim at building strategic visions to guide technological development efforts. For example, the UK Foresight project on "Exploiting the Electromagnetic Spectrum" (EEMS), completed in 2004, identified four rapidly developing areas in this specific S&T domain, which it was thought would represent major areas of economic activity for the coming 10 to 20 years: all-optical data handling, manufacturing with light, electromagnetics in the near field, and non-intrusive imaging. An action plan was devised for each area by its own group, composed of people from business, academia, user communities, and government and other agencies. A five-year review established that the EEMS project had been largely successful in identifying S&T areas that would be important for businesses and these were still relevant after five years. Many of the actions following the project had encouraged discussion of the importance of the four identified S&T areas, although the review found it difficult to quantify the implications of these activities (DTI, 2004).

Several other projects have also had an S&T focus. Examples include expert-based exercises such as "Productive Nanosystems: A Technology Roadmap" (US, 2007; see UT-Battelle [2007]), and the series of Delphi surveys conducted in Korea at five-year intervals since 1994.

Other examples, of more participatory projects, include the "National Nanotechnology Foresight Program" (Russia, 2005; see Gaponenko [2008]) and "Nanotechnology for Podlaskie 2020" (Poland, 2009-13; see Kononiuk et al. [2012]).[5]

Other foresight projects take a more systemic view and aim to build visions for manufacturing, or, more generally, national, regional or sectoral innovation and production systems. For example, "The future of manufacturing: A new era of opportunity and challenge for the UK", a foresight project completed in 2013, considered a wide range of factors shaping the future of manufacturing by looking ahead to 2050 (Box 9.2). This two-year project was a major effort: it produced 37 background reports, mobilised the major UK stakeholders, and involved some 300 industry and academic experts, business leaders and other stakeholders from 25 countries, via workshops organised on three continents (GOS, 2013).

Box 9.2. **The future of manufacturing: A new era of opportunity and challenge for the United Kingdom**

Background

"The future of manufacturing: A new era of opportunity and challenge for the UK" project was launched in 2011, as part of the third cycle of UK Foresight,[1] and was sponsored by the Secretary of State for Business, Innovation and Skills.

Process

This two-year project was run under the personal direction of the Government Chief Scientific Adviser. The Industry High Level Stakeholder Group, with 34 members from businesses, the government, professional associations, NGOs, and trade unions, chaired by the sponsoring politician, provided strategic advice. The project was overseen by a multidisciplinary, nine-strong, Lead Expert Group, chaired by a chairman of a major UK company, and consisted mainly of academics. Besides mobilising the major UK stakeholders, the project also involved some 300 industry and academic experts, business leaders and other stakeholders from 25 countries, via workshops held in Asia, Europe and the United States, as well as using other means of consultation.

Outputs

The written outputs include 37 peer-reviewed technical evidence papers, a final report of 250 pages and a summary report of 54 pages, all made available online. The project considered several factors shaping the key future characteristics of manufacturing by looking ahead to 2050. These include new business models, e.g. the "servitisation" of manufacturing; the extension of value chains; major market trends and opportunities; "onshoring" of production back to the United Kingdom; and the increasing share of foreign ownership. The probable impacts of five pervasive and six secondary technologies are also spelt out, as well as the features of future factories, environmental trends, and skills requirements. Several types of financial gap are also identified. Based on this systemic view of the future of manufacturing, the final report thoroughly explores the policy implications of all these factors and trends. Rather than coming up with naïve suggestions based on simple trend extrapolation, it stresses the need to take an integrated view of value creation in manufacturing; follow a more targeted approach to supporting specific stages of manufacturing based on the value-chain approach, and a systemic understanding of science, technology and innovation policies, as well as industrial policies; and enhance government capability in evaluating and co-ordinating policy over the long term.

Box 9.2. **The future of manufacturing: A new era of opportunity and challenge for the United Kingdom** *(cont.)*

Impact

This project has not been evaluated yet.

1. The United Kingdom was among the frontrunners in Europe to use foresight, starting in the early 1990s. Given the lessons learned, the aims, methods, and organisation of these activities changed whenever a new cycle was launched. The first cycle (1993-98) aimed at identifying S&T priorities for the entire UK research system. The second cycle (1999-2001) was concerned with promoting broader participation in dialogues on business-related issues, mobilising a wider variety of participants, and also broadening the issues considered, especially by putting more emphasis on quality of life. The third cycle (2002-present) significantly changed the scope of analysis to anticipate policy-relevant changes and identify how S&T can serve these direct, sharply focused policy needs (e.g. to tackle flooding, cyber crime and obesity). It restricted the number of projects running at any one time to three or four, as well as the time available to complete a given project (12-18 months). It also became a precondition to have a committed sponsor, i.e. a high-ranking politician or policy maker who is committed to take up the recommendations stemming from a given project. See Georghiou, Keenan and Miles (2010), Keenan and Miles (2008) and Miles (2005) for a thorough analysis of the UK foresight cycles.

The most recent rounds of the Japanese national foresight programme have shifted from an exclusive technological focus to a broader approach, considering e.g. market, health, environmental, skills and ownership issues, too, when presenting a plan for the "Revitalization of Japanese Industry" (Prime Minister's Office, 2013, 2014).

The United States National Academy of Engineering (NAE) published a major report in 2015 taking a broad view of manufacturing: "Making Value for America: Embracing the Future of Manufacturing, Technology, and Work" (Donofrio and Whitefoot, 2015). Unlike the UK foresight process on the future of manufacturing, this US study is based on the work of a smaller group of experts (a committee established by the NAE, staff members and contributions from other S&T experts).

The Advanced Manufacturing Partnership (AMP) has been another important US initiative, launched by the president in 2011. Following a successful first stage, leading to several policy recommendations (PCAST, 2012), its second stage (AMP2.0) was convened in September 2013, yielding further recommendations published in a 2014 report (PCAST, 2014). A follow-up US government-funded initiative is called "MForesight: Alliance for Manufacturing Foresight" (Box 9.3).

In summary, countries have applied a multitude of approaches and methods to identify and prepare for the opportunities and challenges that are likely to be raised by the next production revolution. Given the interrelatedness of technologies, processes and new business models relevant to the next production revolution, a systemic approach to foresight seems more appropriate than a narrower S&T focus. Furthermore, participatory approaches enable various innovation and societal actors to bring together a much richer set of knowledge, experience, values, aspirations, perspectives and strategies to analyse complex technological, economic, social, and potentially environmental changes. Yet, in certain cases, narrower expert-based projects have an important advantage: their results are normally produced more quickly and at a lower cost.

Box 9.3. **US initiatives: The AMP and MForesight: Alliance for Manufacturing Foresight**

Background

The United States launched the AMP in 2011, a national effort bringing together businesses, universities, the federal government, and other stakeholders to identify emerging technologies with the potential to create high-quality domestic manufacturing jobs and enhance US global competitiveness.

Process

The AMP Steering Committee initiated five workstreams on technology development; shared infrastructure and facilities; education and workforce development; policy; and outreach, each with their own objectives. Background reports were produced on these themes. Extensive consultations with stakeholders were organised to identify opportunities for investments in advanced manufacturing with the potential to transform US industry. Four regional meetings were conducted in different states, attended by 1 200 participants from industry and academia. The sixth background report summarised the main insights from these meetings. The second phase of AMP was convened in September 2013.

Outputs

Two major reports were published by the AMP Steering Committee. The first, titled "Capturing Domestic Competitive Advantage in Advanced Manufacturing" (PCAST, 2012), focused on three pillars to create the necessary conditions for maintaining US leadership in advanced manufacturing: enabling innovation (six recommendations); securing the talent pipeline (six recommendations), and improving the business climate (four recommendations). The report's recommendations included: developing a model for evaluating, prioritising, and recommending federal investments in advanced manufacturing technologies; public-private partnerships, including the National Network for Manufacturing Innovation, to focus on advancing high-impact technologies and models for collaboration that encompass technology development, innovation infrastructure, and workforce development; and public intervention to increase private investment in advancing manufacturing in the United States.

The second report, "Accelerating US Advanced Manufacturing" (PCAST, 2014), also used the three pillars identified in phase 1 to organise its 11 recommendations. These were concerned with policy governance (devising a national plan on emerging manufacturing strategy and creating an advisory consortium, as well as a shared National Network for Manufacturing Innovation (NNMI) governance structure); new public-private manufacturing research and development (R&D) infrastructure; processes and standards (e.g. on interoperability of technologies and cyber security); changing the image of manufacturing to attract talent; education and skill development, as well as a system of nationally recognised, portable, and stackable skill certifications; improving the flow of information on technologies, markets and supply chains to small and medium-sized enterprises (SMEs); and reducing the risk associated with scaling up advanced manufacturing technologies via the creation of a public-private scale-up investment fund, improved information flow between strategic partners, government and manufacturers, and tax incentives to foster manufacturing investments. A recommendation on implementation was also added, urging the National Economic Council and the Office of S&T Policy to submit a set of recommendations to the president within 60 days.

Box 9.3. **US initiatives: The AMP and MForesight: Alliance for Manufacturing Foresight** *(cont.)*

Impact

Following the recommendations of the first AMP report, "A National Strategic Plan for Advanced Manufacturing" was published in February 2012; the Advanced Manufacturing National Program Office (AMNPO) was formed as an inter-agency team to co-ordinate and collaborate on cross-cutting initiatives; federal funding for advanced manufacturing R&D was increased by nearly 20% in the 2013 fiscal year; pilot institutes were opened on advanced manufacturing; and the patent system was reformed (further impacts are reported in PCAST [2014]).

As a specific impact, AMP has been followed up by a US government-funded initiative called "MForesight: Alliance for Manufacturing Foresight". MForesight was established in 2015 and aims to "serve as the voice of the national advanced manufacturing community, providing government and industry with information and analyses about emerging technologies, workforce training, and opportunities for public-private partnerships that strengthen US competitiveness." It has six main objectives:

- Identify and prioritise technologies worth developing and expanding.
- Prepare reports on emerging technologies for future investment.
- Identify and share success cases in technology commercialisation and workforce development.
- Communicate opportunities and challenges to business, government, and academia in advanced manufacturing.
- Promote career opportunities in engineering and advanced manufacturing.
- Share technology forecasting results to help the US manufacturing community stay ahead of the curve.

These objectives are to be achieved by organising interactive public workshops, small expert gatherings, and virtual roundtables, publishing reports, articles, and conference presentations, as well as using social media.[1]

1. For further details, see *http://mforesight.org/about-us/*.

Potential benefits of foresight and its roles in devising policies

This section provides an overview of the potential benefits of foresight – by considering its intended and unintended impacts – and analyses six major possible roles for foresight in shaping and implementing policies.

Potential benefits of foresight

As shown by a range of studies (e.g. Havas, Schartinger and Weber [2010] and Cassingena Harper [2016]), foresight can help decision makers cope with an uncertain future. Foresight can aid policy formation by generating reports that analyse the dynamics of change, future challenges and related options for action. Such analysis is used by policy makers as input for issue definition, as well as for designing policies. This can provide the foundations for more robust policies, foster systems thinking, offer a new framing of policy issues, and turn long-term concerns into urgent policy priorities. Foresight can also play a role in making policy implementation more effective by facilitating the mobilisation and

alignment of key stakeholders, supporting policy co-ordination. In this way, foresight can supplement traditional top-down policy instruments, by shaping the mindsets of those participating in the process, thus preparing the ground for complementary actions and strategies.

For these benefits to materialise, foresight needs to achieve impacts in different terms:

- in cognitive terms, to help prepare the mindsets of people for possible changes (new contexts, new socio-economic processes), which would require new ways of thinking
- in procedural terms, by contributing to a change in decision-preparation processes, e.g. by including more, and a wider set of, stakeholders
- in substantive terms, to actually change the content of policies
- in terms of structural and/or organisational changes.

These are the intended impacts of foresight, but it is far from certain that such impacts will actually be achieved. Critical factors and conditions necessary to reap the benefits of foresight are discussed in a later section.

Intended impacts also need to be seen against the backdrop of the policy governance system in which the foresight process is embedded. In essence, a foresight process can either reinforce the existing system of policy governance or contribute to transforming it. In this way, the appropriate design of a foresight process is dependent on prior problem perception. In particular, the frame of reference is key, that is, how the problem area is delineated and whether the existing system of policy governance, or other parts of the innovation system, are to be reinforced or transformed.

In addition to the intended impacts, there can also be unintended impacts, positive and negative. Unintended impacts, by their nature, can rarely be anticipated: they often arise from indirect and unknown influences. For example, the changes in the mindset of policy makers and other stakeholders, which a foresight activity has triggered, may help strengthen or build capabilities of strategic thinking that could be equally useful in other policy domains. The same can be said about new networks built and knowledge created.

The widely known problem of attribution arises when identifying and interpreting the impacts of foresight. Other factors than a given foresight process also affect policies, and foresight may well just reinforce and integrate isolated initiatives that have been around for a while. As a consequence, it is often difficult to observe and measure foresight impacts in a precise way. The problem of attribution is particularly pertinent in relation to far-reaching impacts, such as impacts on economic performance. The paths of influence are multifaceted and indirect, with many other factors coming into play. The timing of expected impacts is also an important consideration, since while some effects may be almost immediate, others may take a long time to arise.[6]

Disentangling how impacts unfold is challenging (Georghiou and Keenan, 2006). In the foresight literature, it is often argued that the "process" benefits are (at least) as important as the "products", i.e. reports, lists of priorities, policy recommendations, roadmaps, etc. (Amanatidou and Guy, 2008). This is because the process is more likely than any report to change the mindsets of decision makers and to help structure new networks (without denying the influence of well-written reports and policy recommendations).[7]

Possible roles of foresight in shaping and implementing policies

Providing the foundations for more robust policies

Foresight explores different possible futures. In uncertain times, thinking in terms of multiple future states is a necessary precondition for devising policies to cope with unexpected developments. The Shell experience of the early 1970s is a well-known example: having considered an oil crisis as one of its possible futures, the company was better prepared than its competitors to tackle this situation once it occurred (Jefferson, 2012; Shell, 2013). Foresight can also make policies more robust by bringing into policy dialogues participants with diverse backgrounds, in order to tap into their wide-ranging accumulated knowledge, complementary experiences, aspirations and ideas. For example, the Finnish governmental foresight report on "Long-term Climate and Energy Policy: Towards a Low-carbon Finland" (2009) used a participatory process involving stakeholders with diverse backgrounds and interests to explore four different scenarios that showed various pathways towards a low-carbon Finland, with each pointing to different implications for industry, consumers and government. Ultimately, the project triggered a dialogue between the government and parliament on the future of the country and provided a foundation for strategies stretching beyond parliamentary cycles.

Fostering systems thinking

In a complex world, phenomena cannot be understood in an isolated manner, but must be seen in context, taking into account a range of viewpoints. Foresight, on account of its participatory nature, is a means to incorporate different perspectives when exploring possible futures and to bring to the fore a range of relevant influences on, and impacts of, the issue in question. The recent British foresight project on "The Future of Manufacturing: A new era of opportunity and challenge for the UK" provides a good example of this. It considers several factors shaping the future of manufacturing to 2050 (Box 9.2). The report explores the policy implications of these factors and trends. It stresses the need to take an integrated view of value creation in manufacturing; to follow a more targeted approach to supporting specific stages of manufacturing based on the value-chain approach and a systemic understanding of science, technology and innovation (STI) policies, as well as industrial policies; and to enhance government capabilities in evaluating and co-ordinating policy over the long term. The process itself can also have systemic impacts, with dialogue strengthening existing, or creating new, networks of actors, and reinforcing a future-oriented way of thinking. The participatory methods used in foresight can also reshape the overall culture of policy making, especially in the domains of education, industrial, and innovation policy.

The US AMP project has also taken a systemic view, stressing the importance of governance structures, processes and standards, skill formation and recognition, financial and other factors constraining investments in advanced technologies, strategy-making capabilities in SMEs, and networking among strategic partners (Box 9.3). Similarly, "Making Value for America: Embracing the Future of Manufacturing, Technology, and Work" (Donofrio and Whitefoot, 2015) has also considered manufacturing in its broader context, as has the study "Revitalization of Japanese Industry" (Prime minister's office, 2013, 2014).

New framing of policy issues

Government bodies tend to be organised along the lines of well-established, and rigidly demarcated, policy domains. In such an environment it is often difficult to find an

appropriate place for cross-cutting research domains or new modes of delimiting them (e.g. shifting from S&T-led to societal challenge-driven research and innovation projects). Foresight processes have the potential to change not only the framing of policy issues, but also to induce organisational innovations. For example, foresight participants might conclude that "silo-thinking" in government circles hinders the orchestration of policy actions that need to be aligned to effectively tackle major issues.

The German Federal Ministry of Education and Research (BMBF) Foresight is a case in point (Box 9.4): it aimed to identify new focal areas in research, defining cross-cutting issues and interdisciplinary topics that require attention. Two novel future fields were called "Human-Technology Co-operation" and "ProductionConsumption 2.0". Both fields obtained high visibility in policy debates and triggered an intense discussion about the future of manufacturing in Germany, eventually contributing to and shaping the concept of what is nowadays called "Industry 4.0". One of the fields was subsequently also mirrored in the creation of a new division in BMBF in 2010, called "Demographic Change and Human-Technology Co-operation".

Box 9.4. **BMBF Foresight, Germany**

Background

The German BMBF Foresight was launched in 2007, with a follow-up in 2012. It builds on earlier foresight activities of BMBF using different methods (Key Technologies, Delphi, FUTUR Process). The BMBF Foresight needs to be viewed in the context of the German High-tech Strategy (aiming to concentrate research efforts on areas of future promise) and the Excellence Initiative (providing top-up funding to leading universities and research centres). The main objectives of the 2007 round were as follows:

- Identify new focal areas in research and technology that the BMBF should address.
- Define cross-cutting issues and interdisciplinary topics that require broader attention.
- Help forge strategic partnerships of various departments within the ministry and different groups of actors in the innovation system, who are able to jointly address the areas and topics identified in a strategic manner.
- Propose priorities for concrete measures to be adopted to promote the fields in question.

Process

The BMBF Foresight, co-ordinated by a team of external experts, employed a combination of analytical and exploratory methods, ranging from expert surveys and participation in critical reflection rounds, to the co-shaping of policy advice. In a first, largely analytical phase, an overview of emerging future topics was produced. It was subsequently consolidated by an online Delphi survey and followed by a series of workshops, designed to deliver the necessary "sense-making". The process delivered 14 future research and innovation topics and seven cross-cutting future fields. Suggestions were also made regarding actors to be involved, partnerships to be formed, and actions to be taken.

Outputs

The outputs of the BMBF Foresight were compiled in a set of main reports: Cuhls, Ganz and Warnke (2009a) and Cuhls, Ganz and Warnke (2009b).

Box 9.4. **BMBF Foresight, Germany** *(cont.)*

Impact

One of the most visible cross-cutting fields was ProductionConsumption 2.0, which integrates future technological and social changes along the entire production-consumption chain. While the future topics could be integrated rather easily in the ministry's strategy and policies, in particular the High-tech Strategy, it was much more difficult to integrate the cross-cutting fields. Addressing cross-cutting issues is difficult in an environment of demarcated terrains of S&T fields and a rather monolithic culture with limited openness to interdisciplinary approaches.

However, the embedding of highly innovative cross-cutting future fields in a process that offers also a number of "quick wins" in terms of more traditional research and innovation topics may have been a wise approach. It allowed infusing some non-conventional insights into a context that was otherwise mainly receptive to conventional research and innovation topics.

Critical factors

The BMBF Foresight was successful in avoiding the fate of several foresight projects in other countries where changes in government significantly reduced the chances of foresight results being taken up by the incoming government. By preparing emerging topics with a significant potential for exploitation, sufficient room was left for political choices in different kinds of strategy formation processes.

Moreover, dedicated efforts to interact closely with the sponsors of the BMBF Foresight were an integral part of project design. The foresight team was expected to engage intensely with different interested departments in the BMBF. While this interaction may have been a meandering search for and discovery of new topics, it strengthened the interactions and debates within and across government departments.

Finally, even the less exploited results of BMBF Foresight turned out to be a valuable resource for subsequent policy making, because they served as an "information reservoir" for further systemic change. In the meantime, experiences have been accumulated in the public administration on how to make effective use of foresight.

Turning long-term concerns into urgent policy priorities

Agenda setting is about deciding which policy issues deserve most attention. Priorities need to be identified, selected, and specified. Whether or not a problem is moved onto the policy agenda is a matter of the perceived urgency of the issue.

Foresight can play a beneficial role for agenda setting in several regards, by making transparent why a seemingly long-term issue may require immediate policy attention. First of all, it contributes to changing the perception of longer-term issues, sometimes turning them into urgent issues. In this way, foresight can be a means to make explicit why long-term issues need to be treated with urgency on today's policy agenda.

Second, and related to the long-term perspective inherent to foresight, novel future-oriented rationales to underpin and justify policy interventions can be developed in the context of foresight, providing arguments justifying government intervention. In the case of the Finnish governmental foresight reports, this effect is enabled and reinforced by the dialogue between parliament and government in developing the reports. Issues of a longer-term nature (e.g. climate change, competitiveness and well-being in society) were positioned

high on the policy agenda due in part to the prominence of the corresponding government Foresight reports.

Finally, developing visions of future conditions often plays an important supporting role in making long-term issues more palpable, because they serve as sources of inspiration and orientation for prioritisation (see Box 9.5 for examples).

Box 9.5. **Manufacturing visions**

United Kingdom

"Constant adaptability will pervade all aspects of manufacturing, from research and development to innovation, production processes, supplier and customer interdependencies, and lifetime product maintenance and repair. Products and processes will be sustainable, with built-in reuse, remanufacturing and recycling for products reaching the end of their useful lives. Closed-loop systems will be used to eliminate energy and water waste and to recycle physical waste." (Excerpt from "A new vision for UK manufacturing" presented in GOS [2013], p. 6.)

United States

"A new generation of networked-based information technologies, data analytics and predictive modeling is providing unprecedented capabilities as well as access to previously unimagined potential uses of data and information not only in the advancement of new physical technologies, materials and products but also the advancement of new, radically better ways of doing manufacturing. (…) Our vision is that such integration via ASCPM [Advanced Sensing, Control, and Platforms for Manufacturing] will increase productivity, product and process agility, environmental sustainability, energy and raw material usage, and safety performance as well as economic performance – and thereby comprehensively improve the competitiveness of US factories of varied sizes and complexity. In particular, broader application of ASCPM technologies has great potential in energy-intensive manufacturing, and integral to use of big-data analytics to drive manufacturing decisions. (…)"

"Visualization, Informatics, & Digital Manufacturing (VIDM) is a set of integrated, cross-cutting enterprise-level smart-manufacturing approaches, leveraging the current advances in information technology systems and tools that will improve US manufacturing competitiveness through end-to-end supply-chain efficiency, unprecedented flexibility, and optimized energy management to achieve error-free manufacturing of customised products and components from digital designs, when needed and where needed. (…) Our vision is that VIDM (…) will rapidly change the way manufacturers use and exchange information to plan, support, source, deliver, and make commercial products in the US. (…)"

"Our vision is that the US will train a workforce that can invent, adapt, maintain, and recycle materials critical to US infrastructure, defense, medical care, and quality of life. This vision will also accelerate the transition from lower to higher TRL/MRL maturity, to enable faster and broader industry adoption." (Excerpts from PCAST [2014], pp. 67-70.)

Facilitating the mobilisation and alignment of key stakeholders

Besides exploring possible futures, most foresight activities also aim to achieve a common understanding of what a desirable future might be. Such visions and, associated to them, more operational roadmaps, can be powerful instruments to assemble key players in a domain around a shared agenda. The main benefit of such visions, roadmaps and strategic agendas is that they help reduce uncertainty about the ambitions of partners and

competitors, and thus assist long-term investment decisions. Moreover, once participants arrive at a shared vision, they can expect that most of their fellow participants would take steps to achieve that chosen future state, and thus align their future actions to the jointly identified favourable future. The first attempt to develop such shared visions for manufacturing at an EU level was the FutMan project (Future of manufacturing in Europe 2015-2020 – the challenge for sustainable development), carried out in 2001-03 (Geyer et al., 2003). By way of scenario development, it explored different manufacturing futures, as well as building blocks of a joint EU vision. Interestingly, the project rightly anticipated technological developments, such as additive manufacturing (3D printing). Results from FutMan nurtured the formation of the MANUFUTURE European technology platform, which brought together the main stakeholders from academia and industry. The MANUFUTURE vision and strategic research agenda was further underpinned by the follow-up project to FutMan, called ManVis.

Supporting policy co-ordination

Foresight usually aims to identify future issues that often cut across established areas of policy interest. By way of involving participants from different policy domains that are likely to be affected by these novel developments, a futures dialogue can be initiated across the boundaries of these fields. This can be a dialogue that contributes to creating a shared perception of emerging challenges, and complementary, if not joint, strategies to address them. Policy co-ordination can be fostered both horizontally (i.e. across policy domains, or between parliament and government) and vertically (i.e. between ministries and executive agencies). The FinnSight 2015 project, conducted in 2006, illustrates both effects (Box 9.6). Its focus was on factors which had significant impacts on Finnish business and society, and on the identification of areas of expertise that would foster well-being and competitiveness. FinnSight 2015 informed the dialogue between government and parliament on these issues. Its results were taken up by the two implementing organisations, the Academy of Finland and the National Technology Agency of Finland (Tekes) in their respective strategy development. The results were also important for the subsequent establishment of Strategic Centres for Science, Technology and Innovation (e.g. CLEEN Oy, the energy and environment cluster).

Box 9.6. **Governmental foresight reports Finland: Finnsight 2015**

Background

The Finnish governmental foresight reports have been prepared by the Prime Minister's Office and a dedicated task force since 1992. These reports are debated in government, then presented and discussed in the Finnish parliament in the second year of each parliamentary term. The 2006 edition of the governmental foresight report – FinnSight 2015 – was dedicated to industrial futures. FinnSight 2015 aimed at identifying future change factors and challenges of research and innovation activities, and analysed the areas of expertise that would foster well-being in society and the competitiveness of businesses by means of scientific research and innovation activities (Academy of Finland and Tekes, 2006).

Process

FinnSight 2015 was jointly implemented by the Academy of Finland and Tekes. It focused on the change factors that may impact on Finnish business and industry as well as Finnish society on a time horizon of 2015, mapped them with current areas of competence in Finland,

Box 9.6. **Governmental foresight reports Finland: Finnsight 2015** *(cont.)*

and suggested areas for future building of focal competence areas. It drew mainly on the work of ten sectoral expert panels, with representatives from business and civic organisations. The panels engaged in qualitative exploration of change factors, as well as in semi-quantitative online assessments. Cross-panel interactions enabled the identification of cross-cutting areas.

Outputs

The main output of the project was a major report to the parliament (Academy of Finland and Tekes, 2006), which served as a basis for parliamentary debates, but also fuelled public debates and strategic thinking in Finnish companies and clusters.

Impact

These governmental foresight reports provide an opportunity to move future issues onto the policy agenda. This happens directly when the reports are taken up in parliamentary and/or public policy debates (and indirectly, when foresight experts contribute to the preparation of the reports). Although it is hard to confirm a direct influence on policy making, there are indications that recent governmental foresight reports have enhanced the awareness and importance of futures thinking in Finland. The institutionalised nature of the reports, the backing from the highest level of the government and the parliament, the methodological soundness, as well as the wide outreach to the best knowledge available in the country, all contribute to enhancing the reports' influence on agenda setting. Given the high-level status of the reports, they also help ensure the continuity of agendas in the course of the shift from one government to the next.

The governmental foresight reports also exert an influence outside of government. FinnSight 2015, for example, has been important for the establishment of Strategic Centrers for Science, Technology and Innovation. Results have also been used to reinforce strategy work at the Academy of Finland and Tekes.

Critical factors

Finland is a country with a well-developed foresight culture, including a high absorptive capacity for foresight. A governmental foresight network connects the many government departments and public agencies with dedicated foresight units, which conduct foresight on a regular basis. There is also a sound awareness of the main barriers and pitfalls associated with government-led foresight processes, and great care is taken to address them. These pitfalls include:

- information overload due to open and shared information
- resistance to making foresight material publicly available
- excessive bureaucratic effort leading to unwillingness to engage
- failure to identify suitable experts and engage with them
- poor quality of source material and analyses
- inconsistent process design
- insufficient continuity of interactions with users of foresight results
- lack of a need for foresight as perceived by society.

Summary of benefits and impacts

In summary, foresight can influence innovation activities and hence economic performance through a web of direct and indirect impacts. Through its process benefits and products (e.g. reports, visions, recommendations, roadmaps) it is likely to shape policy making. However, given the complexity of the pathways of influence – indicated by the sheer number and diversity of actors involved in a foresight process and subsequent policy formation – it would be a demanding task to rigorously establish a clear and direct link between an actual foresight process and its impact on policies.

Furthermore, the potential roles and expected impacts will vary by type of prospective analysis. Participatory processes mobilise a wider set of knowledge, experience, aspirations and world views compared to an expert-based project. Hence, more novel and unconventional ideas can be expected, which can be better substantiated given the diversity of viewpoints, since ideas would be more thoroughly tested and contested from various angles. Furthermore, a deeper understanding of long-term challenges and their social, environmental and economic repercussions is more likely to stem from participatory processes. Policies, therefore, would be better substantiated and their credibility and legitimation strengthened. A wider set of policies could be more consciously orchestrated, increasing the effectiveness of their implementation.

Clearly, prospective analysis focusing on innovation and manufacturing systems would consider a broader set of issues than S&T-centred projects, with benefits for both policy preparation and implementation. Given the complex issues – interrelated technological, economic, societal and environmental opportunities and challenges – brought about by the next production revolution, a systemic approach seems to be more appropriate as a foundation for devising suitable policies. The country case boxes featured in this chapter bear this out. Yet, in certain contexts, an S&T-centred prospective analysis can also be useful. But it should be clear from the outset that different and only more limited benefits and impacts can arise from this approach.

Factors and conditions critical to reaping the benefits of foresight

This section considers the most important factors to keep in mind to reap the benefits of foresight. These include chiefly political and policy factors, as well as various methodological considerations.

A committed client and clear objectives

A fundamental condition for achieving impact is to have a committed client. It is essential to have an organisation or a set of organisations with decision-making competences that would be open to the recommendations stemming from the foresight process and willing to act on the proposals (including acting as a "foresight champion" in case other bodies need to be involved in making decisions). Without this sort of commitment, much of the time and effort participants put into a foresight process would be wasted, together with the public money spent to cover organisational and other costs. By way of example, the second cycle of the UK Foresight programme (1999-2001) had weak impacts for two main reasons: it had too many projects running without a clear focus; and it lacked clients – or project "owners" – who felt a strong need to tackle a perceived policy problem through a foresight process. Learning from this experience, the third cycle, launched in 2002 (and ongoing at the time of writing), has only three to four parallel projects running at any one time, and all these have a "sponsoring" minister who usually chairs the stakeholder group overseeing the project. The

sponsoring minister, therefore, feels ownership and is willing to take up the proposals stemming from the project. Equally good ideas, developed without his or her active involvement, might well be perceived as recommendations by "aliens", and would probably have a lower chance of implementation (Box 9.2).

A coherent project plan should also be devised in close co-operation with the client(s) to determine foresight's focus, main objectives, time horizon, geographic scope, and the choice of participants and methods.

Continued support and sustained efforts over time

Continued support is needed to reap the benefits of foresight activities: it takes quite some time – often several rounds of activities – to affect policies, ways of thinking, policy-making cultures and governance systems. For example, the project "The Future of Manufacturing: A new era of opportunity and challenge for the UK" lasted for two years and required significant resources (Box 9.2). In other cases, a succession of projects was needed: the European MANUFUTURE technology platform has capitalised on the results of FutMan and ManVis (both mentioned above) when defining its vision and strategic research agenda. The MANUFUTURE technology platform has played a role in informing the manufacturing elements of the European Union's Research and Technological Development (EU RTD) Framework Programmes for a new manufacturing paradigm. The Seventh Framework Programme and Horizon 2020 would have evolved differently in the absence of the ManVis and FutMan projects. These strategic dialogues are facilitated now by the Intelligent Manufacturing Systems project, spanning three continents (*www.ims.org*; see also Cagnin and Könnölä [2014]).

In countries where national foresight programmes were one-off initiatives (e.g. Greece and Hungary), opportunities to reap benefits have been constrained. This contrasts with countries that have conducted several foresight cycles over many years (e.g. Germany, Japan and the United Kingdom; see Boxes 9.2 and 9.4).[8]

Learning by doing to absorb insights

Foresight is still a new, unconventional way of thinking, communicating and preparing strategic actions in many countries, and thus learning about foresight is crucial. Readily available reports on actual cases, together with methodological guidelines, would certainly help policy makers, foresight practitioners, stakeholders (as potential participants) and opinion-leaders better understand and assess the relevance of foresight. But deep learning can only occur through practice. As there is no single blueprint for a perfect foresight process, on the one hand, and the challenges to be tackled and the opportunities to be exploited constantly evolve, on the other, the learning process is particularly important. This is forcefully illustrated by the major changes introduced in the third cycle of UK Foresight (Box 9.2). Another telling example is the Japanese national foresight programme, which shifted from an exclusive technological focus in the 1970s and 1980s to a broader socio-technical approach in its most recent rounds. This shift reflects changing perceptions in Japan of the relationship between technology and society.

Supportive organisational and political cultures

The ultimate condition for high-quality and useful foresight is having a deeply rooted foresight culture in place. Nurturing foresight culture is a lengthy and demanding process, which cannot be planned in advance by setting deadlines and milestones. Continued

support to foresight, together with the ensuing learning process, are necessary. For example, since 1992, the Finnish government, under the responsibility of the Prime Minister's Office and supported by external partners, has prepared a foresight report to the Finnish parliament once per parliamentary term. These reports have strengthened long-term thinking in Finland, created a dialogue between government and parliament on future issues of national relevance, and provided a stable strategic framework for policy that goes way beyond election cycles (Box 9.6). In contrast, changes in government have prevented the continuation of national foresight programmes, and thus the creation of a foresight culture, in countries like Greece, Hungary and Turkey.

Close links to decision making – but with intellectual autonomy

To make foresight useful, it should be embedded in the decision-making system (Boxes 9.2 and 9.6). Its timing, relevance to major issues faced by a given society, and co-ordination with other policies are critical. The German BMBF Foresight (2007-09) explored future issues and challenges, to underpin German STI policy, and was closely connected to the German High-tech Strategy. In this way, new focal areas in research and technology were identified, defining cross-cutting issues and interdisciplinary topics that require attention. This co-ordination also helped forge strategic partnerships within BMBF and with actors in the German innovation system (Box 9.4).

It is also important to find an organisational set-up that can ease the inherent contradiction between the need for foresight to be embedded in the decision-making system (to gain political support), and the need to maintain intellectual autonomy (to facilitate original thinking). It is not a trivial task to strike a balance between these requirements, and any solution can only be context-specific. For example, given the legacy of central planning, especially its hierarchical features, the Hungarian government decided that the Hungarian Technology Foresight Programme (TEP) (1998-2000) should be driven by its participants rather than by the government agency that initiated and financed it, and that the programme should enjoy a high level of autonomy. TEP, therefore, was not embedded in decision-making structures. Moreover, the government agency that launched TEP did not have the necessary political clout to convince the major ministries to act on the policy proposals produced by TEP. Only a few recommendations have been implemented, in a slow and non-linear process (Georghiou et al., 2004).

The chosen type of foresight and its main objectives need to "fit" the purpose

For foresight to be effective, it is important to consider the relationship between its design (in terms of focus, methods and level of participation), and characteristics of the system of policy governance in which it is supposed to be embedded (especially the existing decision-making culture and methods, the commitment of decision makers to rely on the results, the availability of methodological skills and experience, and the level of capabilities for strategic thinking). In many cases, a foresight process needs to resonate with the prevailing system of policy governance to be effective. Foresight needs to be compatible with the culture of participation, and respect fundamental institutional and organisational boundaries. This is usually the case in foresight activities that aim to set thematic priorities, but without questioning the structural and institutional conditions in a given area.

However, foresight processes that aim to set thematic priorities need to be clearly distinguished from those that aim to induce systemic change (Havas and Weber, 2017). This is a crucial distinction in the context of the next production revolution, given the

necessity for fundamental changes in organisational structures, institutions and relationships. In such cases, it is more suitable to design transformative foresights that contribute to changing the system of policy governance.

This argument also shows that prior to defining the scope and purpose of a foresight process, a reasonably good idea is needed of the magnitude of the challenges ahead.

Facilitate the use of foresight recommendations

Foresight products should be tailored to the needs and communication modes of intended audiences. For example, short and concise policy briefs for high-level decision makers need to be backed by solid analytical and exploratory reports. The use of social media for diffusing foresight results may be equally important if the wider public is the main target audience. Tailoring foresight results to specific audiences requires specific skills, for instance in terms of translating results into policy briefs.

Very often, the importance of the process of foresight is stressed as delivering additional benefits in terms of networking, mobilisation and strategic co-ordination among participants, but the process is also an important channel to facilitate the use and uptake of foresight recommendations. The participants in the process are best suited to serve as ambassadors of the foresight results (Jarmai, 2015).

Enabling the effective use of foresight in decision making requires good embedding in the organisation (EFFLA, 2012). This embedding has several important facets, including organisational structures and responsibilities (Who is in charge?), the role of foresight in decision-making processes (When does it matter in decision making?), the "futures literacy" of staff members in handling and interpreting foresight activities (Who is competent?) and the access to and exchange with internal and external networks/hubs of foresight knowledge (How can foresight knowledge be sourced?).

Managing a foresight process

The design and management of a foresight process needs to take into account all of the aforementioned aspects, but in particular: i) how to embed foresight in decision-making structures, while maintaining intellectual autonomy; and ii) the appropriate selection of the main approach, participants and methods. Furthermore, it is key to design and implement a communication strategy, tailored to the overall objective and the main target audience (policy makers only versus major stakeholders, civil society organisations and the public at large).

The overall context – in particular the decision-making culture and methods, as well as the availability of the relevant methodological skills and experience – would determine: i) where to locate the management unit; and ii) what roles and responsibilities to assign to external experts, facilitators, and foresight practitioners.

As in the case of any project financed with public funds, the operational aspects – planning a budget and respecting the financial limits, setting appropriate milestones, and keeping to deadlines – are crucial. What is peculiar to a foresight process is the requirement of maintaining a certain degree of flexibility, too. In many cases, the originally identified policy needs, and hence the objectives to be served by the process, are evolving as a result of the process itself: participants arrive at a better understanding of the current situation and of future needs, opportunities and challenges on account of their participation. This means a careful balancing act is needed between two, somewhat contradictory requirements: to set

clear objectives, on the one hand, and keep some room for flexibility, on the other, without jeopardising the timely completion of the process.

Main policy and organisational lessons

Successful innovation processes exploit many different types of knowledge. These pieces of knowledge are generated by various actors and activities, and hence rarely – if ever – are available inside a single organisation. It is, therefore, a major policy task to support the generation, diffusion and exploitation of all types of knowledge, as well as various types of collaborative effort among partners, across sectors and countries. The blurring boundaries between manufacturing and services reinforce this conclusion.

The cases considered above show that foresight, if applied and exploited in an appropriate way, could support policy making at times of rapid technological and socio-economic change. It does this not only by studying how the future might evolve, but also by being an intervention itself. With the help of participatory methods, key actors and stakeholders are mobilised to form shared views about the future, negotiate their future stakes and interests, and agree on joint and coherent actions. These benefits arise also for government, where the emergence of new challenges requires better adjustments and orchestration between different policy domains.

To reap the potential benefits of foresight, several pre-conditions need to be created:

- It is essential to embed foresight appropriately in decision-making processes to make it effective. This requires changes to both organisational structures and strategy formation processes (Box 9.2).
- Foresight processes need to be linked to policy cycles to ensure that futures intelligence is available at the right moment in time.
- Foresight is about more than delivering a report. The participatory elements of foresight are demanding in terms of time and resources, but the interactions among stakeholders and decision makers are essential for triggering change processes in policy governance, society and the economy.
- A sustained effort is needed to create the competences, and a conducive environment, for carrying out foresight effectively and efficiently. One-off exercises are unlikely to yield the expected impacts on policy making. It takes time, and possibly specific measures, to nurture and diffuse future-oriented thinking.
- Some form of institutionalisation – through regular programmes and/or the establishment of dedicated organisations – is needed to create a foresight culture and thus exploit its benefits in a sustained manner. As electoral cycles tend to be significantly shorter than the time horizon of the issues considered by foresight, this condition is of particular importance.
- Without intellectual autonomy in developing new insights, foresight cannot fulfil its key function of pointing to major emerging challenges and opportunities and novel ways to address them.

Notes

1. Major differences of foresight and expert-based (non-participatory) prospective analysis in relation to tackling next production revolution issues are discussed in the next section.
2. Foresight can also assist decision makers in the private sector at firm and sectoral level, e.g. in tackling changes induced by the next production revolution in investment opportunities; co-ordinating

technological, organisational, business model, financial, managerial and marketing innovations; as well as re-organising and co-ordinating international innovation and production networks.

3. For detailed analyses of these country cases consult e.g. Amanatidou (2013, 2014); Cuhls (2004); Cuhls (2013); Cuhls and Georghiou (2004); Cuhls et al. (2009); Georghiou, Keenan and Miles (2010); Georghiou and Keenan (2006); Havas (2003), Keenan and Miles (2009); Könnölä, Salo and Brummer (2009); Kuwahara (1999); Martin and Johnston (1999); Miles (2005); NISTEP (2005); OECD (1996); Salo et al. (2009); Shin, Hong and Grupp (1999); Stanovnik and Kos (2007); and Yokoo and Okuwada (2012).

4. Archetypes are relevant for analytical purposes to support strategy-setting processes, but real-life cases often sit between them. Japan's Robot Strategy (2015), for example, has a strong S&T focus, but it also explicitly considers several cross-cutting issues, such as human resources, development, regulation, as well as the specific features of several sectors, including manufacturing; services; nursing and medical application fields; infrastructure, disaster response and construction; as well as various branches of agri-food businesses. "Nanotechnology for Podlaskie 2020" also had a strong S&T focus, but regional networking and co-operation were major concerns, too. The US Advance Manufacturing Partnership is another example of combining major features of two archetypes: its reports have been produced by expert groups, but 1 200 participants from industry, academia and government have been involved via regional consultation events, and their views and suggestions are reflected in the final report of the project.

5. Given the numerous projects on information and communication technology (ICT), industrial biotechnology, chemicals and pharmaceuticals conducted in many different countries, it is impossible to compile a nearly exhaustive list of these prospective analyses.

6. For a more detailed account on possible intermediate and ultimate impacts, see, e.g. Havas, Schartinger and Weber (2010).

7. Process benefits can also occur in terms of improved decision-preparation processes, as well as more efficient structural and/or organisational set ups.

8. For a concise overview of some of these country cases see e.g. Havas and Weber (2017). For more detailed analyses consult e.g. Amanatidou (2013, 2014); Cuhls (2013); Cuhls and Georghiou (2004); Cuhls et al. (2009); Georghiou, Keenan and Miles (2010), Georghiou and Keenan (2006); Havas (2003), Kuwahara (1999); Martin and Johnston (1999); Miles (2005); NISTEP (2005); OECD (1996); and Yokoo and Okuwada (2012).

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The Next Production Revolution
Implications for Governments and Business
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PART II

Chapter 10

An international review of emerging manufacturing R&D priorities and policies for the next production revolution

by
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This chapter presents a review of emerging trends in manufacturing research and development (R&D) relevant to the next production revolution. It is based on analysis of national government policies, foresight exercises and research strategies in selected OECD countries and other major economies. The review highlights growing attention to the themes of convergence (of research disciplines, technologies and systems), scale-up (of emerging technologies), and national economic value capture (from manufacturing innovation). These policy themes have in turn resulted in manufacturing research programmes and institutions adopting a broader range of innovation functions (beyond basic research), creating closer linkages between innovation system actors, and providing new types of innovation infrastructure (tools, enabling technologies and facilities). Case studies of selected initiatives illustrate the varieties of approaches and contexts across countries. The chapter aims to help inform discussion and stimulate debate about the design and management of manufacturing research institutions and programmes for the next production revolution.

Introduction

This chapter reviews recent trends in national government-funded efforts to support manufacturing R&D. The trends are assessed in terms of: technology research priorities, key themes influencing policy design, and developments in the modus operandi of research institutions and programmes. The chapter is based on a systematic analysis of selected national government policies, foresight exercises and research agency strategies.

The chapter highlights that in designing manufacturing R&D strategies for the next production revolution, policy makers have not only been making decisions about prioritising particular technology research domains but are also designing institutions, programmes and initiatives in an effort to ensure that research results are developed, demonstrated and deployed in industrial systems. The chapter identifies that, in this context, there is growing attention to the themes of convergence (of research disciplines, technologies and systems), scale-up (of emerging technologies), and national economic value capture (from manufacturing innovation). These policy themes have in turn resulted in manufacturing research programmes and institutions adopting a broader range of research and innovation functions, beyond basic research, creating closer linkages between key innovation system actors, and providing new types innovation infrastructure (tools, enabling technologies and facilities) to support convergence and scale-up.

There is increased recognition among policy makers of the need to better understand the forces influencing the future of manufacturing, the consequences for national competitiveness, and the implications for policies to support manufacturing-based economic growth (O'Sullivan et al., 2013). In particular, there is renewed interest across OECD countries to better understand how government-funded manufacturing R&D investments, institutions and initiatives can most effectively drive innovation in the context of the next production revolution. The attention given to manufacturing has grown significantly in recent research and innovation strategies in countries like the United States (NEC and OSTP, 2015), Germany (BMBF, 2014a, 2014b), Japan (CSTI, 2015), the People's Republic of China (hereafter "China") (People's Republic of China, 2016), and multilateral organisations such as the European Commission (EC, 2011). National manufacturing foresight studies and strategies have been recently published in e.g. Sweden (MEI, 2016; Teknikföretagen, 2013), Australia (CSIRO, 2016), and the United Kingdom (Foresight, 2013; BIS, 2012). In-depth roadmaps and strategies for individual high-priority manufacturing technologies have also been produced in countries including Japan (CRDS, 2015), the United Kingdom (AMSG, 2016), the United States (PCAST, 2014), the Netherlands (Holland High Tech, 2015a, 2015b, 2016) and China (MIIT, 2016). Major national manufacturing initiatives are also receiving significant policy attention, including Germany's Industry 4.0 (Acatech, 2013), the United States' National Network for Manufacturing Innovation (AMNPO, 2013), Japan's Robot Strategy (RRRC, 2015); and China's Made in China 2025 (State Council, 2015).

Manufacturing technology research priorities for the next production revolution

The range of technologies that could significantly transform manufacturing is broad and their specific effects remain uncertain (OECD, 2016). However, there is some degree of consensus internationally around broad categories of key emerging technologies with the potential to drastically reshape manufacturing as we know it (IDA, 2012; Dickens, Keely and Williams, 2013; López-Gómez et al., 2013). Technologies such as biomanufacturing, nanomanufacturing, advanced manufacturing information and communication technology (ICT), advanced materials and novel production technologies (e.g. 3D printing) are receiving particular attention in recent governmental studies and strategies. However, identifying specific priorities and designing implementation mechanisms for government-funded research programmes and initiatives is challenging due to the convergence of technologies and the complexity of modern manufacturing. Many of the technology families listed above have a variety of subdomains, draw from diverse academic disciplines, and have a large variety of potential industrial applications. Not only are important emerging manufacturing research domains intrinsically multidisciplinary, but new science and engineering breakthroughs have the potential to drive disruptions across entire value chains. As exemplified later in the chapter, the variety of potential manufacturing technology targets for policy is, therefore, diverse and interrelated.

Government manufacturing research priorities and the approaches to institutional design adopted in different countries vary, reflecting differences in industrial and research strengths (O'Sullivan, 2011, 2016). In Germany, for example, emphasis has been placed on the integration of digital technologies into industrial production machinery and "smart factories", with particular attention to embedded systems, cyber-physical systems[1] and the Internet of Things (IoT) through the high-profile Industry 4.0 initiative (Acatech, 2013). In Japan, the central government has recently placed emphasis on the integration of advanced robotics and artificial intelligence (AI), and the integration of capabilities across specialist supply chains (METI, 2015a, 2015b; CSTI, 2015). In the United States, particular attention has been given in recent national policy documents to accelerated deployment of advanced manufacturing products and processes, often highlighting the importance of emerging science-based technologies (PCAST, 2011, 2014).

Key manufacturing policy themes shaping R&D priorities

The industrial systems context in which new technologies are being developed and used is also becoming increasingly complex. Such systems involve multiple interdependencies between activities, firms, technologies, components, and subsystems which interact to produce products and services (PCAST, 2011; Tassey, 2010; Brecher, 2012). The impact of new technologies (and technological convergence) on the dynamics of value creation and capture across industries is therefore difficult to predict. Embedded systems, for example, are capturing increasing amounts of value in sectors ranging from automotive to aerospace and medical devices (ARTEMIS, 2011).

Furthermore, a number of "megatrends" – e.g. globalisation of value chains, accelerated production life cycles, digitalisation, and changing consumer habits – are acting on manufacturing systems, constantly redefining the sources of competitiveness (Dickens, Kelly and Williams, 2013; López-Gómez et al., 2013). The increasing global demand for customised manufactured products, for example, offers market advantage to those firms with flexible production systems capable of satisfying the requirements of both low and high-volume markets while keeping costs competitive (Brecher, 2012, 2015).

In this increasingly complex and changing industrial context, there is growing policy attention to the themes of convergence, scale-up, and the location of production in high-wage economies. These policy themes are in turn influencing government-funded R&D programmes, public-private partnerships, and the missions of new R&D institutions.

Emerging policy responses to the next production revolution

Common emerging features in new government-funded manufacturing R&D institutions, programmes and initiatives reviewed in this chapter include the adoption of innovation support functions beyond basic R&D (e.g. prototype demonstration, skills training, supply chain development) and an increased focus on "grand challenges" (related e.g. to issues such as sustainable manufacturing, nanomanufacturing, and energy storage). There is also increased emphasis on forming new research partnerships and linkages within the innovation system, with R&D programmes and initiatives, making more explicit requirements for interdisciplinary and inter-institutional collaborations. Similarly, there are increased efforts to improve inter-institutional collaboration and alignment.

The chapter presents a selection of case studies to illustrate the variety of themes and approaches, and to highlight features of high-profile initiatives in some of the countries surveyed. The case studies reviewed are the following: the Cluster of Excellence Integrative Production Technology for High-wage Countries (Germany), the High Value Manufacturing Catapult network (United Kingdom), the Singapore Institute of Manufacturing Technologies (SIMTech, Singapore), the Intelligent Technical Systems OstWestfalenLippe initiative (It's OWL, Germany), the Cross-Ministerial Strategic Innovation Promotion Program (SIP, Japan) and the Pilot Lines for Key Enabling Technologies initiative (European Union, including cases from Sweden and a Belgium-led consortium).

The final section of this chapter presents a summary of key policy themes, approaches and lessons. In this regard, it is emphasised that many research challenges critical to the next production revolution are increasingly multidisciplinary and systemic in nature. Accordingly, policy needs to take account of the increasingly blurred boundaries across fields of manufacturing research. For example, many important research challenges will need to draw on a number of traditionally separate manufacturing-related research domains (such as advanced materials, production tools, ICT, and operations management). Mechanisms should be put in place to support multidisciplinary challenge-led endeavours. Government-funded research institutions need the freedom and mandates to adopt relevant complementary innovation activities or connect to other innovation actors.

Some of the novel policy and institutional approaches responding to the next production revolution have only emerged in the last five years and have not yet been evaluated (or the evaluation results are not in the public domain). Policy makers should design key success metrics for manufacturing R&D programmes and carry out systemic evaluations. In this connection, issues of technology scale-up, technology and research convergence, and system complexity, raise important questions about the choice of evaluation metrics. Traditional metrics may not adequately incentivise efforts to enhance linkages, interdisciplinarity and research translation. Evaluations of institutions and programmes may need new indicators (beyond traditional measures such as numbers of publications and patents) in areas such as: successful pilot line and test-bed demonstration, development of skilled technicians and engineers, repeat consortia membership, small and medium-sized enterprise (SME) participation in new supply chains, and the attraction of foreign direct investment (FDI).

Policy makers also need to be aware of the manufacturability challenges associated with the scale-up of science-based technologies. Investments in applied research centres and pilot production facilities focused on taking innovations out of the laboratory and into production are often essential. Developing linkages and partnerships between manufacturing R&D stakeholders is also critical. This is because of the scale and complexity of innovation challenges in the next production revolution. Meeting these challenges requires diverse capabilities and infrastructure which may be distributed across a wide range of innovation actors. For example, some manufacturing R&D challenges may need expertise and insight from a range of industrial actors, not only manufacturing engineers and industrial researchers, but also designers, suppliers, equipment suppliers, shop floor technicians, and users.

Manufacturing R&D infrastructure also requires the right combinations of tools and facilities to address the challenges and opportunities of convergence and scale-up. Advanced metrology, real-time monitoring technologies, characterisation, analysis and testing technologies, shared databases, and modelling and simulation tools are just some of the tools and facilities concerned. Also needed are demonstration facilities such as test beds, pilot lines and factory demonstrators that provide dedicated research environments with the right mix of tools and enabling technologies, and the technicians to operate them. An example of efforts to provide new innovation infrastructure to address scale-up and convergence challenges is the Pilot Lines for Key Enabling Technologies programme funded by the European Commission.

Emerging manufacturing technology priorities for the next production revolution

There is some degree of consensus internationally around broad categories of key emerging technologies with the potential to drastically reshape manufacturing as we know it (IDA, 2012; Dickens, Kelly and Williams, 2013; López-Gómez et al., 2013). Technologies such as biomanufacturing, nanomanufacturing, advanced manufacturing ICT, advanced materials and manufacturing, and novel production technologies (e.g. 3D printing) receive particular attention in recent governmental studies and strategies across OECD countries. In the context of the next production revolution, identifying more specific priorities for government-funded research programmes and initiatives is particularly challenging due to the convergence of technologies and the increasing complexity of modern manufacturing systems.

Not only are important emerging manufacturing research domains intrinsically multidisciplinary, but new science and engineering breakthroughs also have the potential to change the dynamics of competitiveness across and within industries (OECD, 2016). Solutions to industrial challenges driving productivity and industrial competitiveness will increasingly come from combinations of technologies and involve multiple research domains (OECD, 2016; O'Sullivan, 2011). For example, making next-generation aircraft lighter, quieter and more fuel efficient will require integrated R&D efforts across areas such as high fidelity aerodynamic models, additive machining, advanced composite materials, advanced high-rate airframe production systems, advanced systems integration, advanced batteries and fuel cells, among others (AGP, 2013; NASA, 2016).

Moreover, R&D breakthroughs in particular technologies have the potential for a broad range of impacts across industrial and innovation activities, sectors and application domains. For example, ICT-based research themes are relevant across all levels of

manufacturing systems: material modelling and simulation and smart components; smart factories and additive manufacturing; Industrial Internet and advanced enterprise resource planning; digital manufacturing and design, and big-data analytics. Similarly, R&D in additive manufacturing may underpin engineering solutions for other emerging technologies (from tissue engineering to novel printed electronic devices), and have a range of industrial applications, from health care to aerospace, automotive to creative industries (AMSG, 2016).

Adding to the complexity is the fact that many of the families of technologies listed above have a variety of subdomains and draw from a variety of academic disciplines. Advanced materials research, for example, is an intrinsically multidisciplinary domain with contributions from disciplines including condensed matter physics, chemistry, biology and manufacturing engineering. The list of potential topics for materials research is diverse depending on combinations of material type (e.g. alloys, semiconductors, ceramics), material properties (e.g. optical, magnetic, electric and tensile), the scale at which materials are engineered (e.g. nano-, micro-materials), and the applications or sectors within which the materials technologies are intended to be deployed (e.g. aerospace materials).

Not surprisingly, manufacturing research priorities approaches adopted in different countries (and different national R&D agencies) vary, reflecting differences in industrial and research strengths and priorities (O'Sullivan, 2011; 2016).[2] To illustrate differences in characterisation, language and emphasis found across countries Boxes 10.1 to 10.2 present some recent examples of national manufacturing priority setting. At the end of the chapter, case study examples of recent national programmes and initiatives are presented.

In the United States, the discourse on manufacturing has been largely dominated recently by discussions of "advanced manufacturing" often highlighting the importance of manufacturing information technology (IT) systems or emerging science-based technologies (O'Sullivan and Mitchell, 2012). There is an emphasis on next-generation materials (and novel materials engineering) for manufacturing. United States strategies also highlight nanomanufacturing and "materials genome" multiscale modelling. In an effort to enhance co-ordination across federal agencies and provide a foundation of priorities for public-private collaborations, the United States government has attempted to summarise research on advanced manufacturing technology domains across government agencies, as summarised in Box 10.1 (NTSC, 2016). The exercise included an analysis of technical challenges and opportunities across each technology, and a sampling of current and planned federal programmes and initiatives, with emphasis on promising technologies, defined as "those that suffer from gaps in support for the pre-competitive R&D requisite to unleashing new industries" (NTSC, 2016). Further policy discussion and analysis of strategically important manufacturing technology areas for the United States can be found in various reports of the President's Council of Advisors on Science and Technology (e.g. PCAST [2012, 2014]) (see also Chapter 11).

In the United Kingdom, a study commissioned by the government identified key manufacturing technology areas around which research efforts in the country could be aligned (IfM, 2016). The study was based on a broad consultation with manufacturing stakeholders from academia, government (including government-funded R&D centres), and industry. A novel characterisation of priority manufacturing research domains was used, which distinguished between: i) product technology; ii) materials; iii) management/operational supply chain; iv) enabling technology; v) production technology; and vi) system

engineering and integration (Box 10.2). Additional discussion and analysis of important manufacturing technology areas for the future of manufacturing in the United Kingdom has been offered by the Government Office for Science's Future of Manufacturing foresight exercise (Foresight, 2013).

Box 10.1. **Manufacturing R&D priorities in the United States**

The report "A Snapshot of Priority Technology Areas Across the Federal Government" summarises the following priority advanced manufacturing technology domains of the US Government.

Manufacturing technology areas of emerging importance:

- advanced materials manufacturing
- engineering biology to advance biomanufacturing
- biomanufacturing for regenerative medicine
- advanced bioproducts manufacturing
- continuous manufacturing of pharmaceuticals.

Manufacturing technology areas of established importance, including the mission themes of the US National Manufacturing Innovation Institutes:

- additive manufacturing
- advanced composites
- digital manufacturing and design
- flexible hybrid electronics
- integrated photonics
- lightweight metals
- smart manufacturing
- revolutionary fibres and textiles
- wide bandgap electronics.

Further technical areas of interest identified by the US Department of Defense include:

- advanced machine tools and control systems
- assistive and soft robotics
- bio-engineering for regenerative medicine
- bioprinting across technology sectors
- certification, assessment and qualification
- securing the manufacturing digital thread – cybersecurity for manufacturing.

Technical areas identified as being of interest by the US Department of Energy include:

- chemical and thermal process intensification
- sustainability in manufacturing
- high-value roll-to-roll manufacturing
- materials for harsh service conditions.

Source: NSTC (2016), "Advanced manufacturing: A snapshot of priority technology areas across the federal government".

Box 10.2. **Manufacturing R&D priorities in the United Kingdom**

The report "High Value Manufacturing Landscape 2016", commissioned by the government, attempts to provide a framework to "align manufacturing research efforts in the United Kingdom". The report identifies the following priority cross-sector themes and manufacturing technology areas:

Product technology:

- electronics
- photonics and power electronics
- power-generation technologies
- sensor technologies
- advanced and autonomous robotic technologies.

Materials:

- nanomaterials and nanotechnology
- new composites
- lightweight materials
- biomaterials

other new materials and materials science.

Management/operational supply chain:

- supply chain and business model innovation.

Enabling technology:

- software development and management
- (big) data management and analytics
- IoT
- autonomy
- measurement, metrology, assurance and standards.

Production technology:

- additive manufacturing/3D printing
- advanced assembly
- tooling and fixtures
- surface engineering (finishing and coating)
- remanufacturing
- volume composite manufacture
- biological and synthetic biology processing
- process engineering, capability and efficiency development; control systems.

System engineering and integration:

- integrated design and manufacture
- systems modelling and simulation
- human-machine interface.

Source: IfM (2016), "HVM Landscape 2016".

In Japan, the central government has emphasised in recent policy documents the integration of advanced robotics and AI (METI, 2015a; RRRC, 2015). In this context, the Japanese government has identified a strategic opportunity to lead the world with "robots in the IoT era" and has accordingly focused manufacturing innovation policies to address: global standards for common infrastructure (e.g. operating systems) for robots in manufacturing sites; the utilisation of robots and accumulation of data in various fields such as infrastructure; and relevant AI technologies for robotics which may create value opportunities from accumulated data (RRRC, 2015). Emphasis has also been placed on the importance of innovative design and production methodologies that provide customers with superior levels of customer satisfaction (CSTI, 2015). The manufacture of new products for an ageing population has also been highlighted as providing potential opportunities for Japanese firms (METI, 2015b). Box 10.3 presents key manufacturing R&D priority areas defined in recent national policies by the Japanese government. Further policy discussion and analysis of strategically important manufacturing technology areas for Japan can be found in the various annual manufacturing ("Monodzukuri") reports produced by the Ministry of Economy, Trade and Industry, and analyses published by Japan's Science and Technology Agency (see e.g. METI [2015a]; CRDS [2015a]).

Box 10.3. **Manufacturing R&D priorities in Japan**

One of the themes within Japan's Cross-Ministerial SIP programme is a project called Innovative Design/Manufacturing Technologies, which identifies the following priority manufacturing-related R&D clusters and themes:

Optimised design/manufacturing:

- idea support for general view and product design
- upstream design based on topology optimisation
- bio innovative design
- 3D-anisotropy customised design and manufacturing
- rubber 3D printing and value co-creation.

Upstream delightful design[1]/manufacturing:

- advanced 3D modelling technology platform
- delightful design platform
- interactive upstream design management
- new manufacturing by additive manufacturing.

Innovative materials and 3D moulding:

- molecule adhesive agent
- designable gel 3D printing
- fluidic material 3D printing.

Innovative complex modelling:

- nano-assembly technique of advanced materials
- multiscale/multi-material manufacturing
- high-value ceramics modelling technology
- high-value laser coating
- glass component advanced processing technology.

Box 10.3. **Manufacturing R&D priorities in Japan** *(cont.)*

Combined and intelligent machining technology:

- intelligent machine tool by CAM-CNC integration
- next-generation electrochemical machining
- multi-turret integrated processing machine.

Field-oriented R&D:

- fusion of data mining, GA and rapid prototyping
- snow sports gear using computational chemistry
- metal surface processing based on actual work.

1. Research in this field focuses on flexible design and production methodologies that deliver products and services offering superior ("delight") levels of quality and performance to the consumer.

Source: CSTI (2015), "What is the Cross-ministerial Strategic Innovation Promotion Program?", *www8.cao.go.jp/cstp/panhu/sip_english/46-49.pdf*.

A major recent initiative unveiled by China's State Council, Made in China 2025, is a national plan aimed at the integration of IT and industry that will focus on ten key sectors (State Council, 2015). Made in China 2025 will include measures to eliminate outdated manufacturing activities and promote greater energy efficiency, environmental protection and utilisation of resources (Wübbeke et al., 2016).

The Made in China 2025 strategy is heavily influenced by Germany's Industry 4.0 initiative, and the Chinese Government is exploring co-operation with German institutions to deliver the goals of the strategy (Wübbeke et al., 2016). Contained within the Made in China 2025 initiative is the establishment of national manufacturing innovation centres based on the model of the National Network of Manufacturing Innovation (NNMI) of the United States. Box 10.4 lists the key sectors and manufacturing technology domains prioritised in the Made in China 2025 strategy. Further discussion and analysis of strategically important manufacturing technology areas for China can be found in reports by the Chinese Academy of Sciences and the Ministry of Industry and Information Technology (MIIT, 2016) (see also Chapter 12).

Box 10.4. **Manufacturing R&D priorities in China**

Made in China 2025 establishes ten key priority technology domains:

New generation IT:

- integrated circuits
- ICT equipment
- operating systems and industrial software
- intelligent manufacturing core information equipment.

High-end computerised machines and robots:

- advanced numerical control machine tools
- robotics.

Box 10.4. **Manufacturing R&D priorities in China** *(cont.)*

Space and aviation:

- aircraft
- engines
- airborne equipment and systems
- aerospace equipment/infrastructure.

Maritime equipment and high-tech ships:

- ocean engineering equipment and high-tech ships
- critical systems and components.

Advanced railway transportation equipment:

- advanced railway transportation equipment.

New energy and energy-saving vehicles:

- energy-saving vehicles
- new energy vehicles, including batteries and motors
- intelligent vehicles.

Energy equipment:

- power-generating equipment
- electricity transmission and transformation equipment.

Agricultural machines:

- agricultural equipment.

New materials:

- advanced basic materials, e.g. textiles and steel
- essential strategic materials, e.g. special alloys and high-performance fibres and composites
- cutting-edge new materials, e.g. 3D printing materials and metamaterials.

Biopharma and high-tech medical devices:

- middle and high-end medical equipment.

Source: State Council (2015), *中国制造* 2025 (Made in China 2025).

Key manufacturing policy themes shaping R&D priorities and programme design for the next production revolution

Besides the manufacturing R&D themes above, in the context of increasingly complex modern manufacturing systems, some common policy themes shape national research policies for the next production revolution. These include: the convergence of research domains, technologies and systems; the scale-up of emerging technologies; and production in high-wage economies.

The industrial systems context in which new technologies are being developed and used is also becoming increasingly complex. Such systems involve multiple interdependencies between activities, firms, technologies, components and subsystems which interact to produce products and services (PCAST, 2011; Tassey, 2010; Brecher, 2012). As such, delimiting the boundaries of manufacturing has become increasingly complex.[3] Unlike the vertically

integrated configurations of manufacturing in the 20th century, modern manufacturing is characterised by increasingly complex interdependencies distributed across a range of industries firms, technologies, subsystems and components (PCAST, 2011; Tassey, 2010; Brecher, 2012). This growing complexity means that the scope for innovation in manufacturing is becoming broader, and the ways in which value can be captured from manufacturing more diverse. For example, modern cars are becoming complex electronic systems, including many dozens of microprocessors and other ICT components (Kurfess, 2011), and many millions of lines of code (METI, 2010). This means that non-traditional suppliers of technologies such as embedded systems are capturing increasing amounts of value not only in the automotive sector, but across a range of industrial sectors (ARTEMIS, 2011).

A number of megatrends are acting on these systems, dynamically redefining the sources of competitiveness for manufacturing firms (Dickens, Kelly and Williams, 2013; López-Gómez et al., 2013). These megatrends include phenomena affecting industrial activity at large, such as the increasingly complex and globalised nature of manufacturing; the dramatic reduction in manufacturing timescales associated with the acceleration of technological innovation; and the growing need for sustainable, resource-efficient production. As noted earlier and illustrated later in the chapter, the increasing global demand for customised manufactured products offers market advantage to firms that can develop and deploy flexible production systems capable of delivering products for both low and high-volume markets (Brecher, 2012, 2015).

This system complexity and the relative immaturity of the different enabling technologies pose new challenges for the manufacturing scale-up and industrialisation of new products and related services. Policy makers need to design institutions, programmes and initiatives to ensure that research outputs are developed, demonstrated and deployed in increasingly complex industrial systems. The challenge is not only to pursue emerging high-value opportunities driven by the convergence of technologies and systems, but to ensure that research outputs are scaled up and translated into industrial systems, while also ensuring that domestic industrial systems are able to capture value.

Convergence

Major technologies such as advanced ICT (cyber-physical systems, big data, the IoT), industrial biotechnology and nanotechnology have the potential to radically reshape global manufacturing systems in the coming decades (OECD, 2015, 2016). It is the convergence between these different technologies and the systems based on them that is likely to drive the next production revolution.

In national manufacturing research and innovation policies and strategies, the role of convergence is receiving increasing attention. The term is, however, used to refer to a variety of converging elements, including the convergence of: research domains; emerging technologies; elements of entire industrial systems; and the convergence of the cyber and physical worlds. Box 10.5 discusses the variety of uses of the term “convergence” in the context of the next production revolution and reflects briefly on the implications for policy makers.

One of the most high-profile convergence themes identified in this review is that related to ICT-enabled technologies and systems. Particular emphasis is being placed on the integration of cyber- physical systems (embedded software and sensors, and advanced

measurement and control systems), and the IoT, to manufacturing operations and systems. New "smart manufacturing" systems can be co-ordinated via the Internet throughout entire value chains, allowing rapid development of new products, more efficient logistics, and more customised products and services.

Box 10.5. **"Convergence" in the next production revolution**

The **convergence of research disciplines** has received significant attention from innovation policy makers, most notably the convergence of research at the nanoscale level of materials science, condensed matter physics, and biology (Roco et al., 2002). In recent years the **convergence of technologies**, in particular key enabling technologies such as nanotech, biotech, advanced materials, and ICT, has led to integration at the device-level with technologies combined in ways that offer new functionalities and novel applications (Roco et al., 2013; EC, 2015a). The **convergence of systems**, in particular the novel networking and integration of different elements of industrial and infrastructural systems (e.g. transport, energy grid, factories and production networks) has been enabled by the **convergence of information and communications technologies.** While the concept of convergence is an established part of the broader science, technology and innovation policy discourse (G20, 2016; Midest, 2016; OECD, 2015), the role of convergence in the next production revolution has only recently started to receive attention. In the context of the next production revolution, the following convergence themes have important implications for public manufacturing R&D priorities and programmes.

- **The convergence of key enabling technologies (and the challenges of their manufacturing scale-up).** Many future high-value products and manufacturing systems will depend on a range of technologies (e.g. advanced materials, nanotech, biotech and novel ICT). The combination and integration of these technologies has the potential to enable a range of novel applications and new markets. Some of the potentially most disruptive technologies are based on convergence, e.g. quantum technologies (combining digital IT and advanced materials) and synthetic biology (digital IT and biosciences). The system complexity and immaturity of such technologies poses new challenges for the industrialisation of new products. While converging technologies may offer novel functionality, these functionalities may be challenging to maintain using conventional manufacturing processes or at high production throughput. Technology policies (and analysis) and innovation infrastructure investments (e.g. pilot lines) for the next production revolution will have to address these complexity, scale-up and manufacturing readiness issues.
- **The convergence of production technologies (within hybrid manufacturing systems)** has the potential to underpin high-value manufacturing in high-wage economies. In particular, advanced systems which combine multiple process steps or deploy different production technologies can be used to manufacture products for both niche high-value markets and mass markets by achieving economies of scope and planning. Such hybrid systems can shorten value chains, replacing several production steps with single hybrid processes, and reduce organisational effort by using a single production process. Such hybrid systems are made up of combinations of different technologies, e.g. material engineering technologies (cutting, turning, forming, pressing); and ITC, mechatronics, measuring and sensing technologies. For advanced economies, manufacturing policies and R&D prioritisation should account for the potential of R&D investments to support hybrid manufacturing systems which can be competitively located in high-wage economies.

Box 10.5. **"Convergence" in the next production revolution** *(cont.)*

- **The convergence of manufacturing systems (enabled by advanced ICT and cyber-physical systems)** offers the potential to more effectively integrate and connect manufacturing systems, suppliers and customers. Such convergence will enable more rapid development of new (often "smarter") products, more efficient logistics, and more customised products and services. Advanced ICTs are enabling the integration and convergence of activities along and between three manufacturing dimensions: i) vertically – integrating e.g. tools, unit processes and production lines (often discussed in terms of "smart factories"); ii) horizontally – integrating inter-company value chains and networks (or "smart supply chains"); and iii) along product life cycles – integrating digital end-to-end engineering activities across the entire value chain of a product. R&D policies for the next production revolution will have to consider these system convergence issues when assessing emerging national industrial opportunities, strengths and gaps in relevant innovation capabilities, and the implications for research prioritisation.

The digitalisation of manufacturing is not just about the introduction of new manufacturing-related ICT technologies. Rather, it is a cross-cutting theme disrupting industrial systems at all levels while bringing manufacturing firms, technologies and capabilities closer together. More intense use of digital technologies across manufacturing systems is making more data available and opening new business possibilities for manufacturers. Manufacturing research is also benefiting from new research tools made available by new ICT applications.

Scale-up of novel technologies

An important theme in international manufacturing (and manufacturing innovation) policy documents reviewed in this chapter is the scale-up and industrialisation of novel technologies (PCAST, 2014; EC, 2015b). There are policy implications for a range of different innovation activities related to the term "scale-up", including the engineering scale-up of a novel technology, the production scale-up of a technology-based product, the operational and organisational scale-up of a manufacturing business, or even the scaling up of product value chains or markets. Furthermore, policies related to these different aspects of scale-up have traditionally been treated separately, with programmes typically implemented by different agencies. One of the striking features of some of the emerging programmes addressing scale-up (and illustrated in a number of the case studies in the following section) are the efforts to integrate support, and facilitate linkages and alignment, between different innovation activities.

The term scale-up is used in a variety of ways in the policy documents reviewed as part of this chapter, with different emphases on particular innovation and industrial activities. The semantics of scale-up are discussed in Box 10.6, including suggestions for a broader, unifying conceptualisation of scale-up which could facilitate policy making in this area. A useful and concise definition of scale-up is offered by the influential US report "Accelerating US Advanced Manufacturing" (PCAST, 2014):

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

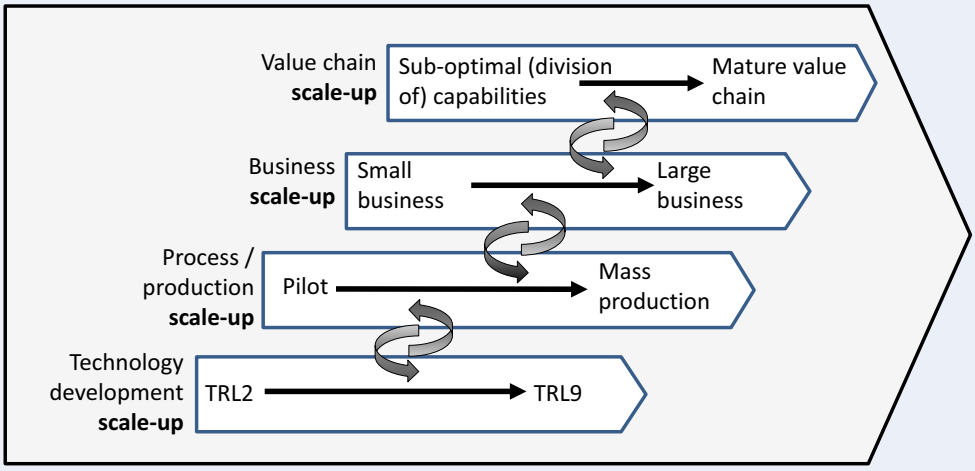
Box 10.6. **"Scale-up" in the next production revolution**

The review of recent international manufacturing R&D policies and programmes suggests the need for a broader conceptualisation of "scale-up" and increased efforts to align and synchronise policy efforts addressing distinct aspects of scale-up. In particular, the review suggests that there is merit in distinguishing between the following dimensions of scale-up conceptualised in Figure 10.1:

- **Technology development scale-up.** For many of the most promising emerging technologies highlighted in international manufacturing research strategies (e.g. synthetic biology, quantum technologies and graphene), the development of novel products faces significant technical uncertainties and risks in the process of transforming a laboratory prototype into an integrated and packaged product demonstrator with the potential for full-scale production. In particular, there are a series of technology readiness levels (TRLs) that need to be achieved.[1] This development process can be especially challenging for devices based on integrated converging technologies, as production processes appropriate for one technology may impact the functionality of another.
- **Process/production scale-up.** Scale-up R&D is not just about product technology innovation, significant R&D effort is also required for novel production/process technologies (e.g. additive manufacturing and laser-based processing) or for adapting processes and techniques for the manufacture of novel key enabling technologies. In particular, many novel production technologies and processes require demonstration of their functionality, applicability and cost-effectiveness at greater production volumes, higher throughput rates and realistic process-line factory environments. In this context, there is a potentially significant role to be played by pilot line programmes, demonstration and testing infrastructure, and intermediate R&D institutes.
- **Business scale-up.** As emerging technology innovation efforts evolve from prototype development to niche/specialist applications to ever larger markets, firms have to expand their technical and operational capabilities, and organisational structures. This can be particularly challenging for smaller innovative firms. A scale-up firm has been defined (Coutu, 2014) as an enterprise with average annualised growth in employees or turnover greater than 20% per year over a three-year period (and with more than ten employees at the beginning of the observation period). Particular scale-up challenges facing rapidly growing manufacturing businesses include "finding employees to hire who have the skills they need; building their leadership capability; accessing customers in other markets/home market; accessing the right combination of finance; navigating infrastructure" (Coutu, 2014).
- **Value-chain scale-up.** The effective industrialisation of an emerging technology also requires the development of new value chains – developing and redistributing manufacturing-related capabilities to support new products, business models and markets. In the next production revolution, manufacturing scale-up innovation may require co-operation across the entire industrial value chain with suppliers of input materials (and components/subsystems) and equipment/tool vendors needing to synchronise their innovation efforts, engaging closely with end users. In this context, there is a significant role to be played by linkage programmes, institutions and diffusion mechanisms (e.g. intermediate R&D institutes, technology diffusion organisations and technology roadmaps).

Box 10.6. **"Scale-up" in the next production revolution** *(cont.)*

Figure 10.1. **The multi-dimensional nature of scale-up**



Source: Author's analysis.

1. The approach involving TRLs is often used to communicate the readiness of a technology (EC, 2015b). Of particular importance to scale-up are TRLs 4-7, which include R&D efforts including technology validation in a relevant manufacturing environment, prototype demonstration in a relevant manufacturing environment, system prototype demonstration in an operational environment.

The scale-up of emerging technologies (advanced materials, biotech, nanotech, etc.) is a common manufacturing research priority in the policies of all the countries reviewed in this study. Many emerging government programmes to support the scale-up of disruptive science-based technologies focus on manufacturability challenges that may require new R&D-based solutions, and novel tools, production technologies and facilities to develop, test and demonstrate emerging applications. In particular, a number of countries are investing in applied research centres and pilot production facilities focused on taking innovations out of the laboratories and into production. Examples of such investments include facilities within the Manufacturing USA institutes, the High Value Manufacturing Catapult Network in the United Kingdom, and the Pilot Lines for Key Enabling Technologies (KETs) funded by the European Commission. The characteristics of some of these institutions and programmes are discussed as part of the case studies in the following section.

The attention given to scale-up is likely to increase due to the competition and the pace of technological change in the next production revolution, which is creating greater urgency among policy makers to "reduce the gap between R&D and deployment of advanced manufacturing innovations … and facilitate rapid scale-up and market penetration of advanced manufacturing technologies" (PCAST, 2012). This in turn is driving the need to more efficiently demonstrate technical feasibility and manufacturability of products embodying novel technologies. The need to bridge the gap between knowledge generation and commercialisation of advanced product and manufacturing-process innovations is high on the international policy agenda. Some of the United Kingdom's Catapult Centres, for example, have been established to address scale-up challenges in areas such as high-value manufacturing, cell therapy and satellite applications and "increase the scale, speed and scope of commercialisation" (Innovate UK, 2015; Hauser, 2010, 2014).

Manufacturing in high-wage economies

Recent national analyses of manufacturing have given careful attention to identifying those elements of modern manufacturing systems with the potential to capture significant value for the domestic economy. Particularly in OECD countries, there have been discussions on the characteristics of production technologies and systems needed to keep manufacturing competitive in high-wage economies.

In addition to automation and the application of advanced ICT across manufacturing systems, the convergence of technologies in the next production revolution is offering new possibilities to drastically increase factory productivity and reduce the length of supply chains (Schuh et al., 2014). New production technologies that combine multiple production steps, for example, can significantly reduce production times. An example of this is hybrid machining centres which can perform laser heat treatment in addition to a machining process during the same operation, drastically reducing changeover times (RWTH, 2015). Applications of selective laser melting (SLM) combined with advanced design tools are enabling the manufacture of small size batches without the high costs associated with traditional process-line set-up and changeover times. Such approaches are particularly important in the context of the growing demand for individualised products (Brecher, 2015; Klocke, 2009), and are expected to enable certain production activities to be retained in high-wage economies. As discussed later in the chapter, a key motivation behind Germany's Cluster of Excellence Integrative Production Technology for High-wage Countries is to develop production technologies that make it feasible for high-value manufacturing operations to remain in high-wage economies like Germany (RWTH, 2015).

Another topic highlighted by some government documents is the potential of some emerging technologies to disrupt the way manufacturers distribute their products, interact with customers and carry out transactions. In particular, Internet-based platform businesses (e.g. those provided by Google or Amazon) are expected to play an important role in capturing value from manufacturing. Such businesses may emerge as potential competitors and/or partners of traditional manufacturing firms (CRDS, 2015b). Efforts have been made by the Japanese government, for example, to identify multidisciplinary research efforts that will be necessary to understand and define platform businesses that allow Japanese manufacturers to capture value from their domestic operations (CRDS, 2015a).

It is important to note that some policy documents point out the potential of technology breakthroughs related to the next production revolution to drive value capture opportunities not only in so-called high-technology sectors, but also in more traditional industries (IDA, 2012). Through adoption of new technologies, it is expected that some of the latter remain viable in high-wage countries even in the face of growing international competition. A good example of research efforts to exploit technologies related to the next production revolution in traditional sectors is provided by the It's OWL consortium discussed later in the chapter.

Emerging policy responses to the next production revolution

The review of policy responses to the next production revolution reveals some emerging trends in the design of major new programmes, institutions and initiatives to tackle increasingly complex manufacturing R&D challenges. Such trends include: increased innovation mission scope (to include innovation activities beyond basic technology research); greater emphasis on new research partnerships and linkages (to pursue synergies between research actors and engage a greater variety of manufacturing stakeholders); and

more attention to new innovation infrastructure (to assemble the necessary combination of tools, equipment and facilities required by the next production revolution). Following a brief discussion of these trends, case study examples of selected initiatives are discussed below to illustrate the varieties of approaches and contexts across countries. It is hoped that these examples will help inform discussion and stimulate the debate about the future design and management of manufacturing institutions and programmes for the next production revolution.

Functions of manufacturing R&D institutes beyond basic research

A striking feature in recent national manufacturing R&D policies and strategies is the creation of programmes and institutions which carry out a wider range of functions than basic research. Some of these functions include: development of advanced skills, access to specialised equipment and expert advice (particularly for SMEs), provision of test beds for new production processes and products, and stakeholder engagement and networks formation. In addition, some of these institutions, in collaboration with economic development agencies, use their technical capabilities as a means to attract FDI and support regional development.

The choice and combination of new functions and activities adopted by national manufacturing R&D institutions is determined by their missions. Because there is a trend for such missions to be more challenge-led, their activities increasingly go beyond addressing only the research component of that challenge. For example, solutions to socio-economic challenges such as ageing, sustainability, energy, and mobility, which are the focus of some recent innovation strategies and manufacturing R&D institutions,[4] require not only research but a wider range of complementary innovation activities.

There is also increasing emphasis on ensuring that manufacturing research addresses industry-relevant problems whose solutions involve more than just research. An example of an institutional response of this type is the Aerospace Technology Institute (ATI) recently established in the United Kingdom. As described in Box 10.7, to help address sector-level innovation challenges, ATI's functions go beyond the funding of R&D (BIS, 2016; ATI, 2016).

Box 10.7. **The United Kingdom's Aerospace Technology Institute (ATI)**

The ATI was created in 2013 as part of the government's industrial strategy at the time (BIS, 2016; ATI, 2016). This strategy targeted aerospace as one of the strategic priority sectors to receive co-ordinated government support for R&D, skills, access to finance, and public procurement. The ATI is a virtual centre of academic researchers and industry experts, supported by a small central office team, with the mission of driving UK innovation leadership in key areas of aerodynamics, propulsion, aerostructures and advanced systems. The ATI runs a research and technology programme (ATI R&T programme) which represents a joint government and private sector investment in supporting the United Kingdom's competitive position in aerospace design and manufacture, mainly focused on large-scale technology and capability challenges over the medium to long-term. The ATI was also tasked with supplying industry and government with high-level technical analysis. Under the ATI research and technology programme, the government provides grant funding for research projects up to 50% of the total project value, and for capital investment projects up to 100% of the total investment value.

Source: ATI (2016), "Raising ambition: Technology strategy and portfolio update 2016".

The selection of functions that national institutions adopt depends, of course, on the particular national innovation system context and specific technological and manufacturing system challenges. For example, in countries without major national metrology laboratories, new institutions may have to develop their own advanced measuring and testing functions. Similarly, countries without established manufacturing advisory service organisations (such as the United States' Manufacturing Extension Partnership) may, to support their broader innovation mission, elect to offer advisory services to small manufacturing firms (e.g. advice on innovation strategies, process improvements, workforce development and navigating standards).

An example of new functions in national institutions is the increased emphasis on industrial skills development in government-funded research centres, such as the United Kingdom's Catapult Centres and the Manufacturing USA institutes. This includes the training of young scientists and the training of company staff. Some programmatic initiatives have been put in place to develop aspects of graduate school-like experience in important emerging science and engineering domains (e.g. the United Kingdom's Centres for Doctoral Training and the German Excellence Initiative Graduate Schools).

Linkages and partnerships between manufacturing R&D stakeholders

While public-private partnerships have received attention from research and innovation policy makers for many years, in recent public manufacturing research programmes and initiatives there is increasing emphasis on the need to enable linkages with relevant actors across manufacturing systems.

Given the scale and complexity of innovation challenges in the next production revolution, the diverse capabilities and infrastructures to address a particular challenge are likely to be distributed across a wide range of innovation actors. Although a number of individual technology domains are important drivers of the next production revolution, the revolution will also be enabled by the convergence of many of these technologies (OECD, 2016). In this context, many recent manufacturing research policy efforts are focused on the design of new programmes and institutions which can bring together the right mix of research and innovation capabilities, facilities and partnerships.

Some manufacturing R&D challenges may require expertise and insights from a range of industrial actors, not only manufacturing engineers and industrial researchers, but also designers, suppliers, equipment suppliers, shop floor technicians, and users. Similarly, some research challenges may require a range of facilities, tools and expertise beyond the scope of any individual research group or institute, but which can be obtained through collaborative linkages with a range of research actors (including e.g. university research centres, national laboratories, research and technology organisations [RTOs], and metrology labs). For example, the United Kingdom's High Value Manufacturing Catapult allows the integration of different centres with diverse areas of technological specialisation to collaborate around important complex challenges that require a mix of technologies and capabilities.

Furthermore, interdisciplinary partnerships across a broader range of research disciplines may also add value to manufacturing research, not only across engineering and the physical sciences, but with business schools and social scientists to ensure that the potential commercial and societal implications of technological development are understood. For example, recent studies in Japan highlight the importance of co-operation between scientists in various fields including engineering, humanities and social sciences to

understand and develop future platform businesses to deliver manufacturing products and related services (CRDS, 2015a). Some newer programmes, such as the Japanese Centers of Innovation (COI), are expected to develop multidisciplinary research agendas as part of the socio-economic orientation of their missions and, where appropriate, mission goals, to develop collaborations with social science and humanities researchers (JST, 2014).

Likewise, renewed efforts are observed to improve inter-agency and inter-institutional collaboration and alignment. Several university-based research centre programmes, e.g. the United Kingdom's Centres for Innovative Manufacturing, explicitly require that funded centres work collegiately with other relevant major institutions (e.g. manufacturing R&D institutes, such as the Catapult Centres, national laboratories and national standards bodies) and influence and work with other stakeholders to ensure acceleration of impact (EPSRC, 2014, 2015). Similarly, programmes, such as the German Research Campus initiative are specifically designed to bring university researchers together with public research institutes and industry in "critical mass"[5] joint research endeavours (Koschatzky and Stahlecker, 2016).

Manufacturing R&D infrastructure: tools, enabling technologies and facilities

Increased attention is being given to ensuring that manufacturing research programmes and institutions provide the right combinations of tools and facilities to address the challenges and opportunities presented by convergence and scale-up. In particular, scaling up of emerging technologies such as advanced materials and synthetic biology and new ICT-enabled manufacturing systems requires a mix of tools and enabling technologies including: advanced metrology, real-time monitoring technologies, characterisation protocols, analysis and testing tools, open databases (e.g. material property databases), and modelling and simulation tools. Importantly, R&D is also required to improve some of these tools, because new research demands improved functionalities and higher levels of precision. For example, some of the key manufacturing R&D themes in the United Kingdom's prioritisation exercise presented in Box 10.2 are categorised as enabling technologies.

Similarly, the European Commission-supported initiative Factories of the Future (EFFRA, 2013) highlights the importance of developing new types of metrology and modelling, simulation and forecasting methods and tools. Some of the prioritised research themes in the initiative include: virtual models spanning all levels of the factory and its life cycle; and modelling and simulation methods for manufacturing processes involving mechanical, energetic, fluidic and chemical phenomena. Innovations across all of these tools and enabling technologies are expected to enable factories to take advantage of the next production revolution (EFFRA, 2013).

As manufacturing R&D progresses to greater scale and levels of complexity, there is often a need for demonstration facilities such as test beds, pilot lines and factory demonstrators that provide dedicated research environments with the right tools and enabling technologies, along with the technicians required to operate them. Such facilities often conduct technical research and demonstration activities, including not only the development of prototypes but also the demonstration and deployment operations at appropriate scale required to validate them. Technology testbeds can help de-risk the adoption of emerging technologies, particularly for smaller manufacturers (PCAST, 2014).

Similar to the discussion of the multiple functions of the manufacturing R&D institutes presented above, such demonstration facilities may also engage in organisational and market-related activities to help firms and other stakeholders in the value chain prepare

for the full-scale commercial production of new products based on research outputs (e.g. by informing product design based on insights from pre-commercial manufacturing demonstration activities and facilitating the development of market relationships with lead customers).

Case studies of manufacturing R&D institutions and programmes: a variety of missions, functions and linkages

Institutional forms and practices are shaped by a range of contextual issues including national innovation priorities, historical strengths and the particular characteristics of the institutional infrastructure in each country (O'Sullivan, 2011, 2016). A range of institutions – including universities, science and economy ministries, intermediate research institutes, R&D agencies and standards development bodies – play critical roles in delivering national manufacturing R&D agendas, both individually and collectively. These institutional actors in different countries vary significantly in configuration, mission, the scale and scope of their activities, and their interconnectedness.

In order to illustrate some of the approaches discussed earlier in the chapter and the diversity of contexts and responses across the countries surveyed, this section presents examples of major institutions, initiatives and programmes responding to trends related to the next production revolution. The case studies presented below are the following: the Cluster of Excellence Integrative Production Technology for High-wage Countries (Germany), the High Value Manufacturing Catapult Centres (United Kingdom), the Singapore Institute of Manufacturing Technology (SIMTech, Singapore), the Intelligent Technical Systems OstWestfalenLippe initiative (It's OWL, Germany), the Cross-Ministerial Strategic Innovation Promotion Program (SIP, Japan), and the Pilot Lines for KETs initiative (European Union, including cases from Sweden and a Belgium-led consortium).

Cluster of Excellence Integrative Production Technology for High-wage Countries (Germany)

One of the flagship research centre initiatives of the German Research Foundation (DFG) related to manufacturing is the Aachen Cluster of Excellence Integrative Production Technology for High-wage Countries. The cluster's research focuses on the potential of integrating multiple production technologies (often with advanced ICT) into hybrid manufacturing systems which produce customised products at cost levels close to those of mass production (RWTH, 2015).

The cluster's activities reflect the importance attached to maintaining production technology leadership within a high-wage economy, as discussed above. Its mission is to develop promising, sustainable production technologies and insights which can make a substantial contribution to maintaining production which is relevant for Germany's high-wage labour market.

The initiative brings together 19 professors from the Department of Materials and Production Technology, and affiliated research institutes, including neighbouring Fraunhofer Institutes. Research projects include virtual, hybrid and self-optimising production systems, and individualised production processes and strategies. The research agenda also aims to develop fundamental insights underpinning a theory of production science. This strand of research brings together aspects of physical production technology and processes with management and economics concepts into a holistic framework to help German firms implement competitive production strategies (RWTH, 2015).

One approach in the theme of individualised production systems is the use of SLM, an additive manufacturing process originally used for generating prototypes, to enable small-batch series production. SLM and similar processes allow the production of parts and components with shapes and geometries not possible with traditional machining methods, thus allowing the manufacture of highly individualised products (RWTH, 2016).

Another key area of research is hybrid production systems that allow various process steps to be carried out on a single machine set-up. A laser heat treatment, for example, can be performed in addition to a machining process in the same machine, thereby eliminating steps, reducing changeover times, and shortening the supply chain (RWTH, 2015). Such integrative approaches have the potential to dramatically improve the productivity of factory operations (RWTH, 2016).

One research area in the cluster that exemplifies the convergence of advanced ICT and production technologies is virtual production. Research projects in this area include efforts to mine, process and visualise data related to all system levels of the factory – from the behaviour of the work pieces in individual manufacturing processes to factory-level logistics – in order to support production managers with decision making.

It is worth noting that although this initiative has been operating for around a decade, its research output and funding has continued to grow following favourable evaluations (RWTH, 2015). This initiative also continues to be at the forefront of digital and networked manufacturing research, and has evolved into one of the major initiatives contributing to the Industry 4.0 agenda in Germany.

High-value Manufacturing Catapult Centres (HVM Catapult), United Kingdom

The United Kingdom's Catapult Centres are applied R&D organisations set up to promote research and innovation through business-led collaboration between scientists, engineers and industrialists (Innovate UK, 2015). Catapult Centres are comparable to the United States' NNMI or Germany's Fraunhofer Institutes. They carry out applied engineering-related R&D in areas such as: high-value manufacturing, satellite applications, offshore renewable energy, the digital economy, transport systems, and energy systems. In addition to their core technology R&D activities, many of the catapults also have a range of other innovation activities, informed and supported by their research capabilities and insights. These complementary innovation activities include: development of supply chains, demonstration and scale-up support, and specialised technician training.

The High Value Manufacturing Catapult (HVM Catapult) is a network of seven centres with distinct but complementary expertise and facilities: the Advanced Forming Research Centre (AFRC), which focuses on metal forming research; the Advanced Manufacturing Research Centre (AMRC), which focuses on advanced machining and materials research; the Centre for Process Innovation (CPI) which focuses on demonstration and scale-up of manufacturing processes for sectors such as pharmaceuticals, biotechnology and printable electronics; the Manufacturing Technology Centre (MTC), which focuses on development and demonstration of new production technologies on an industrial scale; the National Composites Centre (NCC), which focuses on research on technologies for the design and rapid manufacture of high-quality composite products; the Nuclear Advanced Manufacturing Research Centre (NAMRC), which focuses on nuclear and materials technology research; and the Warwick Manufacturing Group (WMG) which focuses on topics such as low-carbon mobility.

This network configuration of the HVM Catapult allows the different centres to form partnerships and research linkages to collectively tackle complex next production revolution challenges requiring a mix of technologies and capabilities. For example, the HVM Catapult has a large-scale, cross-centre project addressing challenges related to high-rate composite automotive component production, bringing together the collective capabilities of the NCC, WMG, AMRC and MTC (HVMC, 2016).

The HVM Catapult has significant demonstration facilities relevant to the next production revolution. For example, in 2014, it launched the United Kingdom's first digital factory demonstrator at the MTC (MTC, 2015). This demonstrator takes the form of an immersive, 3D virtual reality environment which allows users to interact with a "living laboratory" modelled from existing machines. The demonstrator mimics a continuous production environment and allows university researchers, engineers from manufacturing firms, and other manufacturing stakeholders to work collaboratively. The aim of such collaborations is to develop manufacturing innovations to improve productivity, quality and energy efficiency.

The HVM Catapult also offers manufacturing firms access to scale-up facilities (and technician support) which they can use to scale-up and prove-out high-value manufacturing processes (Innovate UK, 2015). For example, in 2016 the HVM Catapult opened the National Biologics Manufacturing Centre, led by the CPI, to help manufacturing firms translate their ideas, research, know-how and market insights into commercial business propositions. The National Biologics Manufacturing Centre offers open access facilities and expertise to help manufacturers develop, prove and commercialise new and improved processes and technologies for biologics manufacture (HVMC, 2016).

The HVM Catapult has a significant supply chain development function building on its manufacturing R&D expertise and insights (Innovate UK, 2015). Not only does the HVM Catapult help develop next-generation supply chains through its strategic support for SMEs, it also offers access to its network of leading suppliers who contribute to key industrial supply chains. For example, the HVM Catapult's NAMRC runs a "Fit for Nuclear" (F4N) service to help UK manufacturing firms prepare to bid for work in the civil nuclear supply chain. F4N lets companies measure their operations against the standards required to supply the nuclear industry and identify necessary steps to close any gaps in technologies and capabilities. F4N was developed with the support of industry leaders such as Areva and EDF Energy, who use F4N to identify potential partners for their own supply chains (HVMC, 2016).

Skills development is an important part of the HVM Catapult's mission (Innovate UK, 2015). New Training Centres have been established at the AMRC and MTC to develop new cohorts of technologists and engineers with the latest cross-sector design and manufacturing skills, based on the latest technologies and techniques, and focused on the management and delivery of innovation. The HVM Catapult is working with all its centres to develop a unified skills development offering for UK industry (HVMC, 2016).

A recent independent review highlighted the Catapult Network's positive contribution to industry in the United Kingdom and called for the establishment of additional centres (Hauser, 2014). In 2016, the government announced its intention to double the funding of the HVM Catapult Network with the aim of expanding its activities to additional areas of the United Kingdom economy (Hauser, 2014; HVMC, 2016).

Singapore Institute of Manufacturing Technology (SIMTech), Singapore

SIMTech is a key actor in the Singaporean manufacturing research and innovation landscape. SIMTech's stated mission is to develop high-value manufacturing technology and human capital to enhance the competitiveness of Singapore's manufacturing industry (SIMTech, 2012). SIMTech specialises in manufacturing-related technologies and themes including: forming, mechatronics, joining, precision measurements, machining, surface technology, and planning and operations management. It collaborates with companies in sectors including: aerospace, automotive, marine, electronics, semiconductor, and medical technology.

One of the most striking features of SIMTech is that, in addition to its core research function, it provides a diversity of complementary innovation services to Singapore-based firms. Some of these include: support to SMEs to develop R&D capabilities; collaborative R&D projects and consortia; supplier development programmes; and the provision of case study-based continuing education courses. Companies can also access the comprehensive array of diagnostic and measurement equipment housed at the institute. SIMTech's mix of services caters for the more immediate needs of the industry while maintaining significant research activities (Yong, 2014).

A particularly interesting feature in the context of the next production revolution is SIMTech's initiatives to help SMEs adopt new technologies, develop new capabilities, and venture into more sophisticated industries. Dedicated supplier development initiatives have been established to help SMEs venture into a selected number of high growth industries where opportunities for local suppliers have been identified. Supplier development efforts typically involve a combination of joint research projects, advisory support and consultancy (including support to adopt relevant industry standards), and access to specialised testing equipment. SIMTech has launched initiatives based on its manufacturing research expertise to develop local suppliers in aerospace, medical technology, oil and gas, complex equipment, and heat treatment industries, among others (SIMTech, 2012).

SIMTEch's centres of innovation are organised around cross-cutting challenges, such as productivity and sustainability, which are central to the next production revolution. These centres aim to engage firms in innovative activities by showcasing the benefits of technology adoption and offering technology transfer services, with a focus on SMEs. One of the centres focuses on cross-cutting precision engineering technologies which are of crucial importance to a range of sectors including electronics, aerospace, automotive, marine, oil and gas, and medical equipment. The centre offers firms access to a range of enabling technologies for measurement and diagnostics, including: optics design and simulation, optical system integration and characterisation, machine vision systems, image processing, 3D surface measurement, 2D and 3D defect inspection, and thermal analysis (PE COI, 2016).

Another activity to support technological upgrading of SMEs is the secondment of research scientists and research engineers to local firms through government-supported industry attachment programmes. Such exchanges of personnel help local enterprises identify critical technologies and build in-house R&D capabilities relevant to their operations (SIMTech, 2012). Furthermore, SIMTech also organises a number of seminars, workshops, fora, and conferences as a way to communicate the latest advances in technology and generate awareness about their potential benefits. In some of these events, larger companies brief SMEs on current and future opportunities for local suppliers.

In terms of skills development, SIMTech offers, in collaboration with the Ministry of Manpower and its agencies, certified case study-based training for manufacturing specialists, engineers, managers, and other industry professionals and executives. These courses draw extensively from the institute's in-house manufacturing expertise and specialised facilities.

SIMTEch's relationship with universities has been strengthened through the establishment of joint research laboratories. Over the last few years, joint laboratories have been established with local universities in emerging areas such as advanced robotics, natural fibre composites, 3D machining, and precision motion systems. Post-graduate research training is offered at these joint laboratories in selected research topics relevant to industry (SIMTech, 2012).

Finally, a particularly interesting feature of SIMTech is the role it plays as an attractor of FDI. In collaboration with the Economic Development Board, SIMTech has engaged with firms considering the establishment of operations in Singapore to develop prospective collaborative R&D programmes as part of the country's value proposition. Some of the latest FDI attraction efforts of this type have focused on the aerospace industry.

Intelligent Technical Systems OstWestfalenLippe (It's OWL), Germany

The It's OWL consortium represents one of the largest investments associated with Germany's Industry 4.0 initiative (It's OWL, 2016a). It's OWL is an alliance of over 170 businesses, universities and institutes, funded through the German Federal Ministry of Education and Research's (BMBF) Leading-Edge Cluster programme. The initiative is hosted at the OstWestfalenLippe region, which has particular manufacturing strengths in mechanical engineering-related sectors and domestic appliances (It's OWL, 2016b).

The focus of It's OWL is on key digitalisation topics at the heart of the next production revolution. The consortium uses the concept of intelligent technical systems to describe systems that arise from the interplay of engineering and ICT. Such systems autonomously adapt to the environment and the needs of users, cope with unexpected situations, are energy-efficient, and reliable (It's OWL, 2016a). It's OWL carries out research projects in areas including: self-optimisation, human-machine interaction, intelligent networking and energy efficiency. Solutions emerging from the consortium's research are expected to impact not only production processes but also the development, deployment, maintenance, and life-cycle management of new products and systems (It's OWL, 2016b).

It's OWL's projects also reflect the pervasiveness of next production revolution technologies across emerging and traditional industries. In addition to research projects with applications in interactive robotics, electric and hybrid vehicles, and intelligent machine tools, the initiative includes projects in areas such as self-optimising solutions for the industrial laundry and furniture industries. Research focused on industrial laundry, for example, aims to improve the interaction between machinery and processes in industrial laundries by using self-optimisation methods and intelligent gripper robots. It is expected that this will increase the productivity of laundries and reduce consumption of energy, water and detergent by around 50% (It's OWL, 2016b).

It's OWL's activities also offer continuous education programmes aimed at updating the knowledge of manufacturing workers in emerging technologies. Older engineers and young professionals are the key target groups. Initiatives include a summer school for graduates and young professionals, and a staff development programme for experienced professional engineers.

Cross-Ministerial Strategic Innovation Promotion Program (SIP), Japan

The Cross-Ministerial SIP programme of the Japanese Government is a national project for science, technology and innovation, spearheaded by Japan's Council for Science, Technology and Innovation (CSTI), Cabinet Office. The SIP is a cross-ministry programme which consists of ten funding strands aimed at revitalising Japan's society and economy, and at enhancing the global standing of Japanese manufacturing industries. Some of these strands focus on manufacturing-related themes, including: innovative design/manufacturing technologies, next-generation power electronics, and structural materials for innovation (CSTI, 2015).

An interesting aspect of the above-mentioned innovative design/manufacturing technologies strand is a research focus on convergence between ICT, design tools and production technologies. Research in this field focuses on flexible design and production methodologies that deliver products and services offering superior ("delight") levels of quality and performance to the consumer. Research projects include production technologies for non-conventional functions or shape, and the application of digital tools (IoT, cyber-physical systems and big data) for developing new prototyping systems for minimising time and costs for product R&D and production (Sasaki, 2015).

Research also aims to improve the linkages between innovation efforts in upstream activities (including R&D on materials and components) and downstream activities (including R&D on products, services and systems), to more quickly respond to the needs of businesses and consumers (CSTI, 2015). It is intended that research results are tested in production quickly in order to accelerate design improvements.

An interesting feature of the SIP programme is that each funding strand is led by a programme director, many with significant private sector experience, responsible for guiding their project from basic research to practical application and commercialisation. In order to access capabilities dispersed across various actors, research projects are encouraged to build linkages between companies, universities, and public sector R&D institutions.

Pilot Lines for Key Enabling Technologies (KETs), European Union

The European Commission's pilot line initiatives for KETs are one of the most high-profile examples of emerging approaches to R&D programmes addressing scale-up and convergence challenges.

The European Commission has identified six KETs as crucial to the further development of the European economy and society – micro- and nanoelectronics, nanotechnology, industrial biotechnology, advanced materials, photonics, and advanced manufacturing technologies (EC, 2012). An important innovation challenge facing KETs is bridging the so-called "Valley of Death", in particular scaling up new KET-based prototypes to commercial manufacturing. The report of the EU High Level Group on KETs called for an EU strategy to support manufacturing-related demonstration pilot line activities for KETs (EC, 2015a) which have: (i) prototyping facilities to enable the fabrication of a significant quantity of innovative product prototypes arising from KETs; and (ii) demonstration and deployment operations at scales appropriate to establish prototype product validation in terms of user performance (EC, 2015b).

In addition to technical research and demonstration activities, pilot lines may also engage in organisational and market-related activities to prepare and inform firms and other value-chain stakeholders for the full commercial production of new KET-based

products (e.g. by informing product design based on pre-commercial manufacturing, and facilitating the development of market relationships with lead customers).

A recent example of an EU KET pilot line, funded under the Horizon2020 programme, is the photonics PIX4life facility (PIX4life, 2017) which focuses on the demonstration and scale-up of silicon nitride (SiN) photonics life science applications. The technical goals for the pilot line initiative include establishing a validated SiN-based technology platform for complex densely integrated photonics-integrated circuits (PICs), and demonstrating the performance of the pilot process in scaling life science applications such as multispectral sources for super resolution microscopy, cytometry and 3D tissue imaging. In addition to its R&D and demonstration activities, the initiative also has some capability-building and supply chain development goals, including the development of a supply chain to integrate mature semiconductor laser sources and complementary metal oxide semiconductor (CMOS) detector arrays with the SiN PICs, and establishing appropriate design kits and tools for the emerging industry.

Technology convergence is also an important issue in the European Commission's KET and pilot line policies. The European Commission has also identified the importance of multi-KETs (mKETs) – i.e. technology applications which integrate and "cross-fertilise" multiple KET and have unique technological functionality or product properties which could not have been obtained with single technologies. Examples of emerging multi-KET application areas are biophotonics, nanomaterials and photo-sensory systems. The mKET pilot line study (EC, 2015b) highlights the innovation challenges of transitioning mKETs from R&D to pilot and industrial scale production, in particular maintaining the functionality of the integrated technologies when produced in high volumes and rates of throughput.

The mKET Pilot Line study highlights the Swedish pilot line Acreo Printed Electronics Arena (PEA) as an mKET Pilot Line Demonstrator (EC, 2015b; PEA, 2017). Acreo is a Swedish ICT research institute which carries out applied research within areas such as photonics for telecoms and nanoelectronics. Acreo's PEA initiative focuses on accelerating the commercialisation of printed electronics and organic bioelectronics. PEA has a pilot production facility called "PEAManufacturing" which provides firms and start-up companies with a manufacturing-like environment where they can learn how to produce printed electronics and organic bioelectronics, test the technologies in their own prototype products and start pilot production. Firms can get access to equipment, pilot process lines, expertise (in a range of scientific, manufacturing engineering areas and project management) as well as links to the regional research and business ecosystem. PEA also acts as start-up facilitator, offering advice, training and micro-production support to new start-up ventures.

Concluding observations: Emerging policy themes, approaches and lessons

This section presents a summary of key policy themes, approaches and lessons relevant to the next production revolution identified in this review of national government policies, foresight exercises and research agency strategies in selected OECD countries and other major economies.

In the context of the next production revolution, manufacturing research policy needs to account for emerging high-value opportunities driven by: the convergence of technologies and systems; the challenges of scaling up and translating research outputs into industrial systems; and the potential to capture value in the national economy. National manufacturing policies and strategies reviewed in this chapter are placing increasing

emphasis on manufacturing research programmes and institutions which adopt a broader range of research and innovation functions (beyond basic research); pursue closer linkages between key innovation system actors; and provide new types of innovation infrastructure and facilities to support convergence and scale-up.

Context: the system nature of the next production revolution

Identifying priorities for government-funded manufacturing research programmes and initiatives is increasingly challenging due to the convergence of technologies and the growing complexity of modern manufacturing. Not only are important emerging manufacturing research domains intrinsically multidisciplinary, but new science and engineering breakthroughs also have the potential to change the dynamics of competitiveness across and within industries. Many of the most important research challenges critical to the success of the next production revolution are increasingly multidisciplinary and systemic in nature, involving converging technologies and manufacturing systems, and engaging a variety of innovation and industrial system actors. In order to assess the impact of R&D investments – and decide where policy efforts should focus – policy makers need to take account of the increasingly blurred boundaries among manufacturing research domains.

In particular, technology R&D programme missions can be too "siloed" if mechanisms are not put in place to support multidisciplinary challenge-led endeavours. For example, many of the most important research challenges will need to draw on a number of traditionally separate manufacturing-related research domains (e.g. advanced materials, production tools, ICT and operations management). Similarly, many government-funded research institutions and programmes have often been constrained to only carrying out research activities without the freedom or mandate to adopt additional relevant innovation activities or connect to other innovation actors. As a result, many government-funded research institutions and programmes are often unable to bring together the right combination of capabilities, partners and facilities to address scale-up and convergence challenges relevant to the next production revolution. As discussed in the case studies and summarised below, some emerging approaches are designed to address these concerns.

Issues of scale-up, convergence and system complexity also raise important questions about the design of key performance indicators (KPIs) and evaluation metrics for manufacturing R&D programmes. Traditional KPIs and metrics may not adequately incentivise efforts to enhance linkages, interdisciplinarity and research translation. Different challenges relevant to the next production revolution will require different research and innovation inputs depending on a range of factors such as industry and technology maturity. For more effective evaluations of the success of institutions and programmes, policy makers may need to develop new indicators beyond traditional KPIs (e.g. numbers of publications and patents) 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 attraction of FDI. Policy makers should avoid one-size-fits-all KPIs that do not account for the systemic nature of the next production revolution.

Convergence

Major technologies such as advanced ICT (cyber-physical systems, big data, the IoT), industrial biotechnology and nanotechnology have the potential to radically reshape global manufacturing systems in the coming decades (OECD, 2015, 2016). Convergence is also

occurring between production technologies, manufacturing systems, and industry sectors. It is the convergence between all of these technologies and systems that is likely to drive the next production revolution. In designing research programmes and initiatives, policy makers need to be aware that convergence is opening new manufacturing R&D opportunities and challenges, with increasing scope for innovation in manufacturing and more diverse ways in which value can be captured from it. The European Commission's research programmes addressing so-called "multi-KETs" (i.e. multiple key enabling technologies) are examples of explicit efforts to pursue new manufacturing R&D opportunities driven by convergence.

Scale-up of manufacturing R&D

The system complexity and relative immaturity of many of the key technologies driving the next production revolution pose significant challenges for the manufacturing scale-up and industrialisation of new products. These converging technologies may be integrated in ways that offer new product functionalities and/or improved performance. However, it may be challenging to maintain these features during production at industrial scale using conventional manufacturing tools and processes. Policy makers need to be aware of the manufacturability challenges associated with scale-up of disruptive science-based technologies which may require new R&D-based solutions and novel tools, production technologies and facilities. Investments in applied research centres and pilot production facilities focused on taking innovations out of the laboratory and into production are one common approach to tackling these challenges. Examples of such investments include facilities within the Manufacturing USA institutes, the HVM Catapult Centres in the United Kingdom, and the Pilot Lines for KETs funded by the European Commission.

Capturing value from the next production revolution

In many OECD countries, manufacturing R&D strategies are placing increasing emphasis on identifying new opportunities for value capture in the domestic economy being created by the next production revolution. For example, there is interest in hybrid production technologies and systems able to produce customised products at mass production prices. The promise of productivity gains driven by the next production revolution (notably Industry 4.0 and, in particular, ICT-enabled advanced manufacturing systems) is also attracting significant attention. Similarly, there is interest in the potential of Internet-based platform businesses to capture value from the online delivery of goods and services and the interactions with customers. Germany's Cluster of Excellence Integrative Production Technology for High-wage Countries, for example, focuses on multiple approaches to make it feasible for high-value manufacturing operations to remain in the country (RWTH, 2015, 2016).

Functions of manufacturing R&D institutes

A striking feature emerging from this review of recently established national manufacturing R&D institutions is that, in addition to their core activities related to technology research, they also carry out a range of complementary innovation activities. These complementary activities include: advanced skills development, access to specialised equipment and expert advice (particularly for SMEs), provision of test beds for new production processes and products, and stakeholder engagement and network formation. In addition, some institutions, in collaboration with economic development agencies, use their technical capabilities as a means to attract FDI and support regional

development. Singapore's Institute of Manufacturing Research (SIMTech) is a good example of an institution that has built on its core research function to provide a broader range of complementary innovation functions.

Linkages and partnerships

Given the scale and complexity of innovation challenges in the next production revolution, the diverse capabilities and infrastructure to address a particular challenge may be distributed across a wide range of innovation actors. While public-private partnerships have received attention from research and innovation policy makers for many years, there is increasing emphasis in recent public manufacturing research programmes and initiatives on establishing effective linkages with relevant actors across manufacturing systems. For example, some manufacturing R&D challenges may require expertise and insights from a range of industrial actors, not only manufacturing engineers and industrial researchers, but also designers, suppliers, equipment suppliers, shop floor technicians, and users. Similarly, some research challenges may require a range of facilities, tools and expertise beyond the scope of any individual research group or institute, but which can be obtained through collaborative linkages with a range of research actors including e.g. university research centres, national laboratories, RTOs and metrology labs. Furthermore, partnerships across a broader range of research disciplines may also add value to manufacturing research, not only across engineering and the physical sciences, but with business schools and social scientists to ensure that the potential commercial and societal implications of technological development are adequately understood. For example, the United Kingdom's HVM Catapult allows the integration of different centres with diverse technological areas of specialisation to collaborate around important complex challenges requiring a mix of technologies and capabilities.

Manufacturing R&D infrastructure for the next production revolution: tools, enabling technologies and facilities

There is increased policy attention on ensuring that manufacturing research programmes and institutions invest in the right combinations of tools and facilities to address the challenges and opportunities presented by convergence and scale-up. In particular, there is emphasis on enabling technologies for manufacturing innovation, including advanced metrology, real-time monitoring technologies, characterisation, analysis and testing technologies, shared databases, and modelling and simulation tools. There is also emphasis on demonstration facilities such as test beds, pilot lines and factory demonstrators that provide dedicated research environments with the right mix of tools and enabling technologies, and the technicians required to operate them. An example of efforts to provide new innovation infrastructure to address scale-up and convergence challenges is the Pilot Lines for KETs programme funded by the European Commission.

Some of the novel approaches responding to the next production revolution highlighted in this chapter have only emerged in the last five years and have not yet been evaluated (or the results of their evaluation are not in the public domain). Early examples of KPIs and evaluation metrics specifically designed for advanced manufacturing research institutes are being developed (see e.g. AMNPO [2015] and BIS [2016]) and some early evaluation is being carried out (see e.g. Hauser [2014]). It is important that policy makers design key performances indicators and success metrics and systematically evaluate and review new manufacturing institutions, programmes and initiatives, in particular those with features

relevant to the next production revolution of the types discussed in this chapter. Future work should focus on building the evidence base, with particular attention given to the appropriate role for government in supporting innovation through manufacturing R&D.

Notes

1. Embedded systems are electronic products, equipment or more complex systems containing computing devices that enable everyday objects to communicate (with other "smart objects") either directly or via a network, such as the Internet. Because embedded systems bridge the gap between the cyber space and the physical world of real things, they are considered to form the "edges" of the IoT (ARTEMIS, 2011).
2. To some extent, manufacturing research portfolios and the terminology associated with manufacturing-related research of a particular country reflect national industrial and innovation strengths and structures (O'Sullivan, 2011).
3. Manufacturing has typically been defined in terms of the process of "converting materials into usable products through human skill and knowledge" (NAE, 2012). Establishments in the manufacturing sector are commonly characterised as those engaged in the "mechanical or chemical transformation of material substances, or components into new products" (NAICS, 2007). Broader definitions highlight the value chain of activities that businesses and workers perform to create a product, deliver it to market, and support it until the end of its life, including R&D, design, production, supply chain management, distribution, marketing, and after-sale services. More recent definitions reflect increasing awareness of the complex, dynamic system-nature of manufacturing. In particular, there is increasing recognition of the complex interactions and interdependencies between industries, technologies and services associated with the manufacture of many modern products, which themselves are often highly complex systems in their own right (PCAST, 2011; Tassey, 2010; Brecher, 2012).
4. Germany's New High-Tech Strategy (BMBF, 2014a), for example, is structured around "mission-oriented" projects addressing key societal challenges. The latter are expected to be "markets of tomorrow", including climate/energy (e.g. CO_2-neutral, energy-efficient, and climate-adapted cities), health/nutrition (e.g. individualised medicine), mobility (e.g. one million electric vehicles in Germany by 2020), security (e.g. more effective protection of the communications network), and communication (e.g. ICT Strategy 2020).
5. "Critical mass", in this context, is a relatively common funding agency term for a large research endeavour which brings together a significant number of researchers with complementary multidisciplinary expertise in order to tackle research challenges of significant scale and complexity that could not be addressed effectively with grants to individual researchers or teams of researchers.

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PART II

Chapter 11

The rise of advanced manufacturing institutes in the United States

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In the decade of the 2000s, US manufacturing employment fell by one-third, 64 000 factories closed, manufacturing capital investment and output suffered, and productivity growth dropped. The US had been systematically shifting production abroad, and studies suggested that the decline in its production capability was affecting its innovation capacity, which had long been viewed as the country's core economic strength. This chapter reviews the origins of the policy response to this dilemma, which came to be called "advanced manufacturing". The chapter traces the way the foundational concepts were developed in a series of reports; explores how a new innovation system response was developed to strengthen the production system; examines the key new policy mechanism, the manufacturing innovation institutes, which is a complex public-private collaborative model to develop new production technologies and processes, combined with workforce education; and, reviews how the new institutes are working, lessons learned as they have started up, and possible enhancements that could expand their policy reach. These new approaches – an advanced manufacturing programme – if implemented, could play a role in strengthening the US manufacturing sector. They could also play a role in moderating the serious social disruption created by the decline in manufacturing.

Introduction: American manufacturing in decline

In the decade of the 2000s, the manufacturing sector in the United States experienced significant disruption.[1] The Great Recession of 2007-08 accelerated the changes but they were structural, not simply caused by the economic crisis. There was adversity in manufacturing jobs, capital investment, output, productivity and trade. One-third of the US manufacturing workforce lost their jobs in the course of the 2000s. This economic disruption led to social disruption (Bonvillian, 2016). While most Americans once assumed they were becoming one big middle class, instead, a working class facing declining incomes is now in clear, angry view. Manufacturing had long offered a path to the middle class for American high school-educated men. But from 1990-2013, the median income of men without high school diplomas fell by 20%, and of men with high school diplomas or some college education fell by 13% (Kearney, Hershbein and Jacome, 2015). In parallel, income inequality had significantly increased in the past decade and a half. The decline in manufacturing was not the only cause, but it was a significant one. Driven by these economic realities, a new manufacturing effort between federal and state governments, industry, and universities materialised in the wake of the Great Recession. It was an effort to bring systematic innovation back to US manufacturing and promote what was known as "advanced manufacturing". This chapter discusses how this policy emerged, its elements and, particularly, its centrepiece, a network of new advanced manufacturing institutes, which numbered 14 by the beginning of 2017.

The decade of the 2000s

The US manufacturing sector had a devastating decade over 2000-10 and has only partially recovered (Nager and Atkinson, 2015). The decline is illustrated by five measures: employment, investment, output, productivity growth and trade imbalance (Atkinson et al., 2012).

Employment. Over the past 50 years manufacturing's share of gross domestic product (GDP) shrank from 27% to 12%. For most of this period (1965-2000), manufacturing employment generally remained constant at 17 million; in the decade 2000-10 it fell precipitously by almost one-third (with 5.8 million jobs lost), to under 12 million, recovering by 2015 to only 12.3 million.[2] All manufacturing sectors saw job losses over 2000-10,[3] with sectors most prone to globalisation, led by textiles and furniture, suffering massive job losses.

Investment. Manufacturing-fixed capital investment (plant, equipment and information technology [IT]), if cost adjusted, actually declined in the 2000s (down 1.8%), the first decade this has occurred since data collection began.[4] Investment declined in 13 of 19 industrial sectors and stagnated in 3 others (Stewart and Atkinson, 2013).

Output. Data shows US manufacturing output growth of only 0.5% per year over 2000-07 (before the Great Recession), and zero output growth per year over 2007-14, despite the gradual overall economic recovery following 2008 (Scott, 2015). Manufacturing output growth was lower than both GDP growth and population growth. In the Great Recession

itself, manufacturing output fell dramatically, by 10.3% over2007-09, followed by the slowest economic recovery in total GDP in 60 years (Atkinson et al., 2012).

Productivity. Recent analysis shows that the productivity growth rate in manufacturing averaged 4.1% per year during 1989-2000, when the sector was absorbing the gains of the IT revolution. However, over 2007-14 productivity growth in manufacturing fell to only 1.7% a year.[5] Because productivity and output are tied, the decline and stagnation in output cited above helps explain the lower level of productivity increase in the later period. Compared to 19 other leading manufacturing nations, one major study found the United States was 10th in productivity growth in manufacturing and 17th in net output growth in the period 2000-10 (Atkinson et al., 2012). So, taken together, the evidence suggests that productivity gains were less than initially estimated, and so were not the significant cause of the one-third decline in manufacturing employment many thought (Scott, 2015; Atkinson et al., 2012). Political economist Suzanne Berger has noted that many economists thought manufacturing was like agriculture – a story of relentless productivity gains allowing an ever smaller workforce to create ever greater output. Berger found the analogy with agriculture to be simply incorrect in recent years because the assumed levels of productivity gains were in fact lower (Berger, 2014). This means one has to look at an overall decline in the sector itself to discover why manufacturing lost nearly one-third of its workforce in a decade.

Trade imbalance. In 2015 the United States ran a trade deficit (balance of payments in imports over exports) in manufactured goods of USD 832 billion.[6] As of 2015, that total included a USD 92 billion deficit in advanced technology products, a deficit which keeps growing.[7] The idea that the United States could keep moving up the scale to produce higher-value products – that it could lose commodity production and keep leading production of advanced technology goods (see e.g. Mann [2003]) – is undermined by this data. Gradual growth in the services trade surplus (USD 227 billion in 2015)[8] is dwarfed by the size and continuing growth of the deficit in goods: the former will not offset the latter any time in the foreseeable future. So having a highly developed services economy does not allow the United States to dispense with a production economy.

To summarise, during 2000-10 US manufacturing employment fell, manufacturing capital investment fell, manufacturing output fell, manufacturing productivity was lower than previously assumed, and manufacturing trade was seriously imbalanced, with the strong US services sector offering only a limited offset. Overall, the US manufacturing sector has been hollowing out. The post-2009 manufacturing recovery from recession has been the slowest in history: while there has been some manufacturing job and output recovery, these remain below pre-recession levels. The underlying structural problems in the sector still need addressing.

Trade effects

Paul Samuelson sounded an alert in a 2004 article attacking mainstream views of the net benefits of trade: he found such views "dead wrong about the assumed necessary surplus of winnings over losings." Instead "the new labour-market clearing real wage has been lowered" by a realistic view of trade dynamics, creating "new net harmful US terms of trade." (Samuelson, 2004). Autor, Dorn and Hanson (2016) have substantiated a picture of problematic trade effects (see also Preeg [2016], Meckstroth [2014] and Dahlman [2012]). They found that the trade relationship between the United States and the People's Republic of China (hereafter "China"), formed in the 1990s and formally recognised in the 2001 WTO agreement, affected many labour-intensive industries in the United States, where significant

numbers of those jobs shifted to China. This shift came at a heavy cost to US workers when many blue-collar jobs in particular disappeared, with the communities where they worked also suffering economically. Autor, Dorn and Hanson (2016) also show that the adverse consequences of trade can be enduring, with the United States as yet unable to get past the shock of the loss of millions of jobs in numerous communities.[9]

As economics Nobelist Michael Spence has noted, "Globalization hurts some subgroups within some countries, including the advanced economies… The result is growing disparities in income and employment across the US economy, with highly educated workers enjoying more opportunities and workers with less education facing declining employment prospects and stagnant incomes." (Spence, 2011). Just as manufacturing employment was a key to enabling less educated workers to enter the middle class after World War II, the loss of manufacturing jobs has been a key element in the decline in real income for a significant part of the American middle class in recent decades. Obviously, the 2008-09 Great Recession, when manufacturing was a leading victim, played a role, but it appears that there is no getting around the effects of trade, which have been longer term.

The innovation perspective

If the picture on the US production side is problematic, what of innovation? The United States retains what is probably still the world's strongest early-stage innovation system, although competition in this area from other countries is growing. Any manufacturing strategy must seek to use this comparative innovation advantage. However, in the past, research and development (R&D) in the United States has had only a very limited focus on the advanced technologies and processes needed for production leadership. This is in sharp contrast to the approach to manufacturing R&D taken by Germany, Japan, Korea, Chinese Taipei and now China, which have "manufacturing-led" innovation (Bonvillian and Weiss, 2015). As discussed in more detail below, the United States – its government agencies and other organisations – had simply not applied the innovation system to what turns out to be a crucial stage in innovation – production, particularly initial production using complex, high-value technologies. This stage involves highly creative engineering and design, and often entails rethinking the underlying science and invention: production is part of the innovation process and not severed from it. Missing this link between production and innovation created a major gap in the US innovation system.

The reach of manufacturing into the American economy

Manufacturing remains a major sector of the US economy: it represents approximately 12.1% of US GDP, contributing USD 2.09 trillion to a USD 17.3 trillion economy and employing 12.3 million in a total employed workforce of some 150 million.[10] On average, manufacturing workers are paid at least 20% more than workers in services and non-manufacturing (Helper, Kruger and Wial, 2012). Manufacturing firms employ some 64% of US scientists and engineers, and these firms perform 70% of industrial R&D (Tassey, 2010, citing Bureau of Economic Analysis [BEA] and National Science Foundation [NSF] data). Thus US manufacturing strength and the strength of its innovation system are directly linked.

Meckstroth (2016) develops new data that tell a story of the importance of manufacturing as part of the complex value chain of US companies. This study found that the manufactured goods value chain, plus manufacturing for other industries' supply chains, accounts for about one-third of GDP and employment in the United States. This study further found that the domestic manufacturing value-added multiplier is 3.6, which is much higher

than conventional calculations. In other words, for every dollar of domestic manufacturing value-added destined for manufactured goods for final demand, another USD 3.60 of value-added is generated elsewhere in the economy. Finally, for each full-time job in manufacturing dedicated to producing value for final demand, there are 3.4 full-time equivalent jobs created in non-manufacturing industries: this job multiplier is far higher than in any other sector. Higher value-added production industries appear to have even higher multipliers. To summarise, Meckstroth's central finding is that the current estimates of manufacturing's share of GDP are partial and seriously understated. Given its reach into the US economy, new policy perspectives on manufacturing decline appear to be necessary.

Advanced manufacturing emerges as a policy priority at the federal level

As Barack Obama was sworn in as president in January 2008 he faced the Great Recession, the first economic slowdown since the 1930s to approach Depression levels of economic decline, the highest long-term unemployment rate since the Depression and over 15 million unemployed (Bureau of Labor Statistics, 2012). As described above, manufacturing, along with construction, was the most heavily impacted sector. In 2008-09, the administration focused on getting Congress to pass, and then implementing, an economic stimulus bill, focused on short-term, "shovel-ready" job creation, and salvaging a bankrupt auto sector. With the stimulus in place, the administration began to focus on some of the underlying structural problems in the economy: manufacturing policy was high on that list.

The historical precedents for a federal manufacturing role

The federal role in the US innovation system largely stems from the Second World War, where it embarked on a series of major wartime technology efforts working in close concert with industry, industry laboratories and university researchers.[11] At the end of the war this system was dismantled, but President Roosevelt's science czar, Vannevar Bush, worked with him to retain a key element that had emerged at scale during the war: federally funded research universities supported by research agencies at the federal level. The problem at the end of the war was not the US manufacturing system: this mass-production-based system dominated world production. Instead, the challenge was creating a foundational research base building on what had begun during the war. So when the United States built a federally supported innovation system, it was organised around early-stage R&D. Innovation in production was not even considered. As noted above, when Germany and Japan entered the post-war period, they had a different problem, rebuilding their industrial bases, so they focused on manufacturing-led innovation while the United States focused on R&D-led innovation.

Because production of new technologies is an important part of innovation systems, there was a major gap lurking in the US system, as suggested above. The US ran into trouble from this gap during its competition in the 1970s and 1980s with Japanese manufacturing. Japan had innovated in production technologies and processes to create quality manufacturing, capturing large parts of the auto and consumer electronics sectors. The US, content with its mass production model, had entirely missed this advance, and had to scramble for years to catch up.

As part of its catch-up to Japan's advances in production, the United States created a series of new programmes in the 1980s to supplement its basic research emphasis (Bonvillian, 2014):

- The **Bayh-Dole Act** was passed in 1980, and was the first of the new generation of competitiveness legislation. Historically, the federal government held the rights to the

results of federally funded research. Since the federal government did not undertake technology implementation, this intellectual property sat on the shelf. The act shifted ownership of federally funded research results to the universities where the research had been performed, giving universities a stake in its commercialisation, and spurring an entrepreneurship role for university researchers.

- The **Manufacturing Extension Partnership** (MEP) was authorised in 1988, based on the success of the longstanding US agriculture extension programme. It aimed to bring the latest manufacturing technologies and processes to small manufacturers around the nation, since small firms were increasingly dominating US manufacturing, advising them on the latest manufacturing advances to foster productivity gains. MEP formed extension centres in every state, which states cost-shared, backed up by a small commerce department headquarters staff charged with programme evaluations and transmission of best practices to the centres.
- The **Small Business Innovation Research** (SBIR) programme offered competitive R&D grant funding to small and start-up companies, administered by the 11 largest federal R&D agencies as part of their research programmes. These grants aimed to ensure that small, high-tech, innovative businesses were a part of the federal government's R&D efforts.
- The **Advanced Technology Programme** (ATP) was formed in 1988 in the Department of Commerce's National Institute of Standards and Technology (NIST) programme to fund a broad base of high-risk, high-reward R&D undertaken by industry. While it had success nurturing later stage development projects for new technologies, Congress gradually defunded the programme in the 2000s, viewing it as overly interventionist federal "industrial policy."[12]
- **Sematech** was formed by a consortium of semiconductor fabricators and equipment makers that by the late 1980s were facing imminent demise from strong competitors in Japan. Because semiconductor technology was key to many defence systems the effort had national security implications, so industry funding was matched by the Defense Advanced Research Projects Agency (DARPA). The consortium focused on major efficiency and quality improvements in semiconductor manufacturing. After five years production leadership was restored and DARPA funding ended in 1996. Sematech continued as a key technology planning organisation to keep the industry on a Moore's Law roadmap. The Sematech model is the closest to the organisational approaches that came to be considered in the 2010-12 period.

But these manufacturing-related programmes remained modest and of limited scale because by the early 1990s the United States, relying on advances from its strong R&D-oriented innovation system, was able to lead the launch of the IT revolution. The United States entered a decade of strong GDP and productivity growth, and largely forgot about manufacturing. Emerging manufacturing competition from China, exacerbated by the Great Recession, forced another wake-up call.

White House 2011 advanced manufacturing report

Against a backdrop of economic crisis and a series of new studies,[13] a small group in the White House Office of Science and Technology Policy (OSTP) had been developing a report urging a strong new commitment by the administration to manufacturing, as a longer-term more structural approach than short-term economic stimulus.

The final 2011 OSTP report, entitled "Ensuring American Leadership in Advanced Manufacturing", defined advanced manufacturing as the manufacture of conventional or novel products through processes that depend on the co-ordination of information, automation, computation, software, sensing, and networking, and/or which make use of cutting-edge materials and emerging scientific capabilities (PCAST, 2011). The report argued that federal investments in advanced manufacturing could enable the United States to regain its status as a global leader in manufacturing, which would yield high-paying jobs, support domestic innovation, and enhance national security. However, the failure to lead in production would potentially jeopardise the nation's ability to develop the next generation of advanced products. Retention of manufacturing would enable new synergies, whereby design, engineering, scale-up, and production processes would provide feedback for product conception and innovation, helping to generate both new technologies and new later-generation products.

The report proposed "shared facilities and infrastructure" where small and medium-sized manufacturing firms could develop new production approaches embodying productivity gains, allowing these firms to more rapidly prototype, test and make new products. The report recommended federal applied research support of advanced manufacturing processes that cut across a range of production sectors to enable producers to more rapidly develop new US-made sectors. This included, interestingly, "Supporting the creation and dissemination of powerful design methodologies that dramatically expand the ability of entrepreneurs to design products and processes." (PCAST, 2011, p. iii).

The 2011 OSTP report further recommended developing partnerships between industry, universities and government, with government and industry co-investments, which could help develop emerging technologies. Included in the recommendations was a proposed "advanced manufacturing initiative" across government agencies that could link to industry-university collaborations to develop more detailed approaches. Importantly, issuance of the report, and the simultaneous announcement of a new public-private partnership to pursue this initiative, locked in a White House commitment to a manufacturing innovation strategy.

The Advanced Manufacturing Partnership begins: June 2011

The president announced, on 24 June 2011, an "Advanced Manufacturing Partnership" (AMP) and named Dow Chemical's chief executive officer (CEO) and Massachusetts Institute of Technology's (MIT) president as co-chairs of this industry-university-government consortium.

On the industry side, the AMP included CEOs from a diverse group of major companies, spread across industrial sectors. On the university side, the AMP included presidents of five universities with strengths in engineering and applied science.[14] On the government side, the chair of the National Economic Council (NEC) and the acting commerce secretary co-led a cross-agency effort. Within the White House, NEC and OSTP staff provided leadership. The agencies deeply involved in supporting the effort were the NIST in the Commerce Department, the NSF through its Engineering Division, the Department of Energy (US DoE) through its Energy Efficiency and Renewable Energy office (EERE), and the Department of Defense (US DoD) (through its Mantech programme). The President's Council of Advisors on Science and Technology (PCAST), based in OSTP, provided an administrative home for the effort and formally issued the AMP report (although it was written by the AMP team).

AMP1.0 July 2012 report: "Capturing Domestic Competitive Advantage in Advanced Manufacturing"

The first AMP report called for an "advanced manufacturing strategy" based on a "systematic process to identify and prioritise critical cross-cutting technologies" (PCAST, 2012). That process should lead to an ongoing strategy, which in turn could be translated into more detailed technology roadmaps for each of the new technology paradigms. The report also developed a framework for prioritising federal investments in such technologies based on such factors as national need, global demand, US manufacturing competitiveness in the field and technology readiness. It also called for an assessment of the willingness of industry, university research and government to commit to the technology, such as whether, in the case of government, the technology could meet national security needs (PCAST, 2012). Polling groups of manufacturers and university experts, the report developed a preliminary priority list of technology areas to be pursued: advancing sensing, measurement, and process control; advanced materials design, synthesis, and processing; visualisation, informatics, and digital manufacturing technologies; sustainable manufacturing; nanomanufacturing, flexible electronics manufacturing; biomanufacturing and bioinformatics; additive manufacturing; advanced manufacturing and testing equipment; industrial robotics; and advanced forming and joining technologies. Again, strategies for these technology areas were to be developed over time into true technology roadmaps that were to be co-ordinated across technologies and periodically updated.

To nurture these technologies, this first AMP report called for building R&D efforts around them. Significantly, it also called for the creation of manufacturing innovation institutes (MIIs), comprised of small and medium-sized firms linked to larger firms, backed by multidisciplinary university applied science and engineering, with cost-shared funding support from both government (federal and state) and participating industry. The idea was a translation into a US context of the successful German Fraunhofer Institutes, 60 of which were spread across Germany, in a wide range of technology focus areas. The US version was to be an industry-led model, shared and cost-shared, like the Fraunhofer Institutes, across small and medium-sized firms, with a supporting university technology development role in applied science and engineering, and with support from both national and state government. The US institutes were to operate at the regional level to take advantage of area-specific industrial clusters, but be able to translate their technology and process learning to manufacturers at a national scale. To facilitate this national translation and to tie together the MIIs around jointly learned lessons, the report proposed a National Network of Manufacturing Innovation Institutes (NNMI). These policies were guided by a vision that there was a gap between R&D supported by government and the product development role of industry. A support system for the stages of technology development, technology demonstration and system/subsystem development – technology readiness levels (TRL) 4-7[15] – was simply missing. The network's role was to fill that gap.

The MIT study: "Production in the Innovation Economy" (PIE), 2010-13

The MIT study PIE was published in 2013, after the AMP 2012 study. While there had been a number of major manufacturing studies in this period, MIT's two-volume report, under development starting in 2010, was perhaps the broadest and most far-reaching, and its research findings significantly influenced the AMP reports.

At heart, the PIE study asked one major question: what production capabilities are needed to support innovation and to realise its benefits in high-quality jobs, strong firms,

business creation and sustainable economic growth? (Berger, 2014).[16] Assuming what economists had long accepted, that innovation is required for economic growth and productivity, the PIE study examined "what it takes to sustain innovation over time and what it takes to bring innovation into the economy." (Berger, 2014, Chapter 7). The PIE process reviewed innovation in products, in processes, in types of firms, in other nations, through technology advances and workforce improvements. The focus that the PIE study helped create in the United States, starting in 2010, was on the application of innovation theory to production. While such theory had been applied many times to particular new technologies, such as in IT, innovation theory had not been systematically applied to the US production system. It was a new look. The five overall areas the PIE study examined in turn led to a series of new policy approaches for each.

The PIE report found a globalised world economy in which research, development, production and distribution had become fragmented and dispersed. Enabling this was a shift in corporate ownership and control, where major, vertically integrated corporations began to divest many of their attributes, from R&D to production to post-sales services. Few fully vertically integrated firms remained. They had been reorganised under pressure from a financial services sector that, beginning in the 1980s, required firms seeking capital to reorganise around "core competency", with leaner, "asset light" firms receiving higher stock valuations by the weeding out of their less profitable divisions (Berger, 2014). One of the first functions at many firms to go outside corporate boundaries was manufacturing, which reduced capital obligations and "headcount" commitments. Manufacturing units often shifted abroad. IT advances helped enable this development: computer-driven equipment using digital specifications allowed firms to produce goods without the vertical linkages previously required. The reduction of trade barriers worldwide and China's entry into the World Trade Organization were further enablers of distributed production.

The shift to core competencies in firms, plus competition from abroad, thinned out the manufacturing ecosystem. Support for training systems, inducements for suppliers to adopt best practices, and the depth of supply chains all declined. While major firms had once supported strong industrial laboratories that undertook basic and applied research, basic research at the industrial level dropped, and applied work became much more focused on incremental development that could translate to the bottom line. Expansion was more frequently accomplished through mergers and acquisitions, not through in-house innovation. Previously, large, vertically organised firms had created numerous "public goods", e.g. in research, training, and the transfer of technology and expertise to suppliers, that populated the ecosystem with spillovers that helped small and medium-sized firms. But private production of such public goods now declined.

To summarise, larger firms dropped their vertical model, focused on "core competency," went "asset light," and distributed their production. The resulting gaps in the ecosystem could be characterised as market failures because the declining network of complementary capabilities made firms less capable as they found it harder to access the former industrial commons. Small and medium-sized firms were increasingly what the PIE study termed "home alone", operating in a thinned-out industrial ecosystem. The end of local banking also hit small and medium-sized firms. As financial services pursued national and international investment models, the home town banker with personal knowledge of those he or she was lending to was disappearing. Capital became harder to find, so small and medium-sized firms had more difficulty in obtaining the resources to scale up their production of

innovations. In other words, the industrial ocean that the Main Street manufacturer used to swim in began to dry up.

The PIE study also told a technology story. A major example was studied in depth to evaluate the possible implications of innovation for production. This was a case study on a mix of challenging technologies to enable "mass customisation" (Berger, 2014). Mass customisation entailed small-scale, local production using 3D printing and computer-driven standards with equipment that could make small lots of uniquely designed products as cost efficiently as uniform mass production. The case study elaborated on the technologies to enable this and found the model possible. It would mark a dramatic turn in the nature of production. This "advanced manufacturing" innovation model for production was found promising, creating an organising principal for restoring the manufacturing ecosystem. The study also told a story of problems in obtaining financing for "hard" technology start-ups as they scaled up for manufacturing: the venture capital system simply did not fit these firms, which required longer term and higher capital support than venture capital companies were attuned to (Reynolds, Semel and Lawrence, 2014).

Finally, the PIE study examined workforce needs. Earlier reports tended to query senior management in manufacturing, who unfailingly complained that they were not able to find skilled workers.[17] But if this sector had shed almost one-third of its workers in the decade of the 2000s, was there really a shortage? The PIE study questioned firms' hiring officials not about the availability of skilled workers but more pointedly about how long it took to fill jobs. The answer was that open positions were being promptly filled in 76% of cases (Osterman and Weaver, 2014). There was no skills emergency. But 24% of manufacturing establishments still reported some level of long-term vacancies. This is where the story became more interesting. A subset in the group experiencing long-term vacancies tended to include newer firms, working on more advanced technologies. These firms did face skill constraints. So if PIE was proposing the adoption of advanced manufacturing driven by new technologies and processes, it was clear that the training system would need to adapt to meet this challenge. The recommendations called for "a new skill production system" requiring employers to engage with community colleges, supporting government programmes at the federal, state and regional levels, and supporting intermediary organisations to help manage the linkages and communications.

Overall, the PIE study called for rebuilding a thinned-out industrial ecosystem. New shared facilities and capabilities across firms and industrial sectors were required to bring more innovation into production. Larger firms and government could perform a convening function, comparable to what Sematech had achieved in semiconductor production in the late 1980s and 1990s. It found that a similar collaboration across firms, education institutions and public intermediaries could also work in the skills training context.

AMP2.0 October 2014 report: "Accelerating US Advanced Manufacturing"

The president "rechartered" the AMP in September 2013 to work on implementation of the 2012 report and to identify new strategies building on the earlier AMP1.0 report. This project marked the next major step in advanced manufacturing policy development.

Since the administration was in the process of creating manufacturing institutes, the AMP2.0 report focused on complementary policies (PCAST, 2014). In the area of technology policy, this report called for a national strategy co-ordinated across public and private sectors for "emerging manufacturing technologies". This strategy would include "prioritised

manufacturing technology areas" which should be used to guide a "portfolio" of federal "advanced manufacturing technology investments." To show that this concept could work, the AMP2.0 group surveyed priority emerging manufacturing technologies and developed their own pilot strategies in three technology areas identified by the study as priorities: advanced sensing, control and platforms for manufacturing; visualisation, informatics and digital manufacturing; and advanced materials manufacturing. The administration subsequently worked to create manufacturing institutes to cover these identified priority areas, drawing on the strategies.

Federal investment was not solely to focus on manufacturing institutes. The establishment of R&D support for manufacturing technologies was needed, and additional institutional entities were called for. These mechanisms included manufacturing centres of excellence, as well as technology testbeds which could act as additional infrastructure backing up the institutes. The R&D and support infrastructure were to be developed co-operatively with industry. An advanced manufacturing advisory consortium was called for to provide private sector input on both the strategy and the R&D infrastructure. The report foresaw that to thrive over time the manufacturing institutes had to be connected to a robust R&D effort and infrastructure in order to foster ongoing advances in the technologies the institutes were supporting. In addition, a "shared NNMI" was called for to network the manufacturing institutes so that ideas, technologies and best practices could be shared across institutes. Shared processes and standards to spread implementation of new manufacturing technologies were also recommended.

In the area of workforce training and development the report recommended a national system of portable, stackable manufacturing skill certifications. These would be used by employers in hiring and promotion, and would help production workers obtain readily transferable and recognisable skills. The development of online training and accreditation programmes with federal support through job training programmes was also proposed. AMP2.0 members themselves developed extensive manufacturing training toolkits and playbooks, as well as a pilot apprenticeship training programme

The report also had a work group on "scale-up policy" examining the difficulties faced by small and medium-sized firms and start-ups in obtaining financing for scaling up production of new innovations. This problem had been identified in the MIT PIE study, and extensive discussions were held with venture capital, corporate venture and private equity firms, as well as other possible sources of growth financing. An ambitious public-private scale-up investment fund was envisioned to finance pilot production sites for new technologies. In addition, a better system for linking manufacturers with potential strategic partners who could aid in the scaling up of production was called for. The scale-up gap became one of the key focus areas of the report. Although the administration subsequently proposed new scale-up financing, in a period of limited resources, Congress did not respond.

Congressional manufacturing legislation: 2014

The final saga in this summary of the major reports and efforts behind advanced manufacturing concerns Congressional legislation. For government action to be enduring, it must be authorised by Congress, and a foundation of regular and relatively stable appropriations must follow. As can be seen, government commitments ultimately flow from law and the corresponding funding, not administrative fiat.

Particularly after 2010, Congress was afflicted with deep ideological divisions, including within the majority Congressional party, and a corresponding inability to move legislation. Despite this divide, Congress was able to pass significant manufacturing legislation on a highly bipartisan basis. This speaks to the political power of manufacturing, through the employment and relatively high wages it still commands, in American politics. After passing the House, and moving through Committee in the Senate, the manufacturing bill was added to a large annual omnibus appropriations bill to fund all the government agencies for the fiscal year. This was a "must pass" bill. As a "minibus" attached to the omnibus, it passed the House on 11 December and the Senate on 13 December 2014.

The legislation[18] authorised the establishment of a network of 15 regional manufacturing institutes across the country, each focused on a unique technology, material or process relevant to advanced manufacturing (House Committee on Science, Space and Technology, 2014) which was to form a Network for Manufacturing Innovation. NIST was to be the lead agency in forming the network, but could collaborate with other federal agencies in selecting and awarding funding institutes, which must be cost-shared by industry and state or local governments. NIST was required to develop and periodically update a strategic plan for the network of institutes. It was also required to link the institutes to the existing MEP that offered efficiency and technology advice to small manufacturers in every state, and required institutes to take on education and training roles.

Of course, in the meantime a series of manufacturing institutes had already been established, sponsored by the by the US DoD's Mantech programme and the US DoE's EERE office. The bill's idea of having NIST leadership for new institutes did not match the reality of what was already evolving. But the bill amounted to an important Congressional validation of the manufacturing institute model. The bill also called for the creation of a network to connect the institutes, for the development of an ongoing manufacturing technology strategy, and gave NIST the authority to sponsor its own institutes when it could round up sufficient appropriations to do so, which it was able to accomplish in 2016. A notoriously divided Congress had come together on a bipartisan basis to bless advanced manufacturing and a creative model of MIIs to get there.

The Advanced Manufacturing Innovation Institute model

A key goal of the MIIs was to fill a gap in the US innovation system for manufacturing: to create a space where advanced manufacturing could evolve through a collaboration between industry (both small and large firms), universities and government (Molnar, Linder and Shuart, 2016). The federal award to each new institute over a five-year period was to range from USD 70 to USD 120 million. The consortium of firms, universities and state governments backing each new institute was required to contribute at least a one-to-one match to leverage the federal government's investment.

The complex institute model

This was a very complex model for the new institutes. The government's role here was not to make a single research award to a principal investigator to undertake a science research project according a carefully delineated plan in the grant application, which is the usual government R&D role. Instead the government's role had to relate to a large, complex mix of industrial firms that varied widely across numerous sectors and sizes, along with academic institutions that ranged from major research universities to regional universities to community colleges. And state governments were to be co-investors, with industry and

the federal government supporting particular related projects. With the possible exception of Sematech,[19] the federal government had not tried anything like this before.

The participant mix for the institutes was complex and so was their task list:

- "create" new production technologies, processes and "capabilities"
- serve as "proving grounds" to test new technologies and related processes
- support efforts to "deploy" for new production innovations
- "build workforce skills" to enhance production and processes for the emerging technologies.

The overall goal was to enable domestic manufacturing around the focused innovation area of each institute to flourish.

There was also to be a network of manufacturing institutes layered above the individual institutes, to enable cross-collaborations and exchanges of best practices. As advanced manufacturing took hold, a small or medium-sized manufacturer probably would not have just a 3D printing problem, it would have a range of future production challenges across a number of new fields, from digital production technologies to advanced materials. Production is also anchored in regions which tend to focus on particular production areas – e.g. cars in the Midwest, aerospace on the coasts and pharmaceuticals in the Northeast. While the institutes needed to have regional depth, they also had to translate their advances and know-how to manufacturers nationally. The institutes and their NNMI network had a major overarching assignment which was both regional and national.

The agencies take the lead: 2012

The institutes did not emerge from a highly organised, well-timed governmental assembly line. They were scraped together. As noted in the previous section, after the 2010 elections there was a deep ideological divide in politics. Rather than wait for a divided Congress to authorise and fund a new programme, which could mean waiting forever, the new administration cajoled the agencies to start to set up institutes, using existing authority with funding scavenged from other areas. As a result, the agencies were in charge, and starting in 2012 picked focus areas for manufacturing institutes that matched their missions. The AMP1.0 report had assumed that the institute focus areas would come from a bottom-up model, with industry leading in selecting focus areas. Instead, there was a top-down approach, and the agencies decided the focus areas based on their own missions, not an overall manufacturing mission. This was not all bad. Since the agencies did the selection and were in charge, they chose focus areas they cared about that would serve their agency missions, potentially making this a more sustainable project over time, not a White House-imposed mandate. Over time, however, agency perspectives broadened. The top areas that industry had identified as its priorities in the AMP1.0 and AMP2.0 reports turned out to mesh over time with agency missions. And the agency lead tended to enhance agency buy-in for the new programme.

The US DoD had the most money so supported the most institutes. The US DoD had a rich history of wartime governmental economic interventions to assure technology and industrial outcomes, which no other agency dared politically to consider. The US DoD's Mantech programme, based in the Office of the Secretary of Defense, with branches in each of the military services, dated back many decades, but had not been a significant defence programme since at least the end of the Cold War.

But with the manufacturing institutes, Mantech now had a national mission overseen by the president himself.[20] However, Mantech did not get a big new influx of funding, because of the Congressional impasse over all new programmes, so it had to rely on an existing small staff and stretch existing budgets. Mantech's role was complicated by the reality that a number of connected programmes in the military services also had to be brought aboard. These separate programmes had separate service priorities, reporting systems and needs, and did not all exist in the Secretary of Defense's office.

One early development helped create interest in the US DoD. When the proposals came in for the first manufacturing institute on 3D printing (or additive manufacturing) established in 2012, the match proposed by industry and states to Mantech funds was not simply one-to-one: the institute proponents were ready to significantly overmatch. This was eye-opening to Mantech staff, as they could get major additional leverage on their investments. This opportunity for leverage, and to work on major new technologies at a larger scale, had not happened in Mantech in recent memory. Suddenly Mantech staff had a force multiplier.

The story at the US DoE was different. The US DoE's EERE office worked on applied energy technologies with industry. It had long had an industrial efficiency programme: industry had long been a major energy user and there were major clean energy gains, as well as potential savings for industry, from conservation and more efficient energy technologies. Importantly, in the absence of carbon pricing legislation in the United States, new energy technologies would have to compete on price with established fossil technologies. Unless production costs could be brought down for these new technologies, they would never get to the marketplace. Advanced manufacturing therefore became an important EERE priority.

The story at the Commerce Department's NIST was different, too. Despite NISTs' strong involvement in AMP, and its co-ordinating role among agencies, it was unable to secure Congressional funding until 2016 to establish a manufacturing institute. When it did, NIST avoided a "top-down" agency selection of the institute focus area, seeking "bottom-up" focus area proposals from industry and university consortia. NIST also played a supportive role in obtaining Congressional approval of the 2014 advanced manufacturing legislation, which focused on NIST.

While NSF was the fourth major federal government actor, its basic research focus limited its ability to form manufacturing institutes. However, NSF's Engineering Division was very involved in the AMP reports, led NSF programmes on advanced manufacturing research, and oversaw a number of engineering research centres focused on manufacturing technologies. In addition, NSF's Advanced Technology Education (ATE) programmes emphasised advanced manufacturing education and training in community colleges.

The manufacturing institutes: 2012-16

The manufacturing institutes are the centrepiece of the advanced manufacturing programme. The group of institutes was originally labelled the NNMI, but renamed ManufacturingUSA in 2016. The range of their technical focus is particularly notable, while Germany's "Industry 4.0" advanced manufacturing initiative emphasises the Internet of Things, i.e. only one of the areas addressed by the US institutes. The institutes' wide technical embrace is suggestive of how far-reaching an advanced manufacturing revolution could be. This technical breadth may be what is most interesting about the US approach, and deserves enumeration.

As of the beginning of 2017, there were a total of 14 institutes, eight sponsored by the US DoD, five by US DoE and one by NIST, with the option that NIST could add another in 2017 if funding proved available.[21] Two of the institutes and their technology areas are described below, namely the first institute, America Makes – the National Additive Manufacturing Innovation Institute and, in the form of a more detailed case study, the Institute of Advanced Composites Manufacturing Innovation. A description of all the remaining institutes is provided in the annex to this chapter. The annex describes, the Digital Manufacturing and Design Innovation Institute (DMDII), the Lightweight Innovations for Tomorrow (LIFT) institute, which addresses lightweight and modern metals, Power America, for next-generation power electronics, the Institute for Advanced Composites Manufacturing Innovation (IACMI), the American Institute for Manufacturing Integrated Photonics (AIM Photonics), NextFlex, for flexible hybrid electronics, Advanced Functional Fabrics of America (AFFOA), the Smart Manufacturing Innovation Institute, the Rapid Advancement in Process Intensification Deployment Institute (RAPID), the Advanced Regenerative Manufacturing Institute (ARMI), the Institute for Reducing EMbodied Energy And Decreasing Emissions in Materials Manufacturing (REMADE) and the Advanced Robotics Manufacturing (ARM) Institute.

America Makes – National Additive Manufacturing Innovation Institute[22] – was the first manufacturing institute, announced in 2012, headquartered in Youngstown, Ohio, with a regional base in the Cleveland, Ohio to Pittsburg, Pennsylvania corridor, and focused on 3D printing technologies, also known as additive manufacturing. Additive manufacturing is a process of joining materials to make devices using three-dimensional computer model data, layer upon layer. This compares with subtractive manufacturing which relies on traditional machine tools. It typically uses powder forms of metals or polymers, and even biological tissue. A competitive advantage of additive manufacturing is that parts can be fabricated as soon as the three-dimensional digital description of the part is entered into the printer, potentially creating a new market for on-demand, mass-customised manufacturing. Importantly, these processes minimise material waste and tooling requirements, as well as potentially compressing stages in the supply chain. These printing processes enable entirely new components and structures that cannot be cost-effectively produced from conventional manufacturing processes such as casting, moulding, and forging. Additive manufacturing might compete directly with mass production techniques if the speed of layering is significantly improved, although major progress on this is required. Meanwhile, additive manufacturing will be employed to replace parts on site, to reduce the need for parts inventories, and to create much more complex and intricate components beyond the reach of current processes. Additive manufacturing could be a key enabler of mass customisation (the ability to create small lots of personally designed products at the cost of mass produced goods). This could localise production, enabling scale-down of production for the first time in the history of production.

Selected after a highly competitive process, state and industry funds from the America Makes consortium, matched with support from the Air Force Mantech programme and other agencies, formed an approximately USD 100 million programme. The institute's mission is to accelerate additive manufacturing and its widespread adoption by bridging the technology gap between research and technology development and deployment. America Makes' roster of participants includes 53 companies, both small and large, concentrated mainly in the Midwest but stretching across the nation. These include firms organised around 3D printing technologies, like 3D Systems, major aerospace firms, like Boeing, Lockheed Martin, United Technologies and Northrup Grumman, where 3D printing may prove transformative, and a

large number of small production firms. Some 36 universities are involved, ranging from major research universities to community colleges. Over 20 other organisations participate, from state agencies to industry associations.

The America Makes consortium has developed a detailed technology roadmap organised around design, materials, process and supply chain adoption. There is also an additive materials "genome" effort to enable step change improvements in the time and cost required to design, develop, and qualify new materials for additive manufacturing, using novel computational methods, such as physics-based and model-assisted material property prediction tools. The institute has worked to create an infrastructure for the sharing of additive manufacturing ideas and research, on development and evaluation of additive manufacturing technologies, on engaging with educational institutions and manufacturers for training in the new field, and on linking small and medium-sized firms with resources to enable them to use additive manufacturing. A major emphasis of American Makes has been on R&D and technology development projects. An example is a joint university-industry effort between the University of Texas at El Paso, with Lockheed Martin, Boeing, Honeywell and Draper Laboratory in Cambridge to embed a suite of electronics manufacturing technologies into 3D printing processes, such as precision machining, thermoplastic extrusion, direct foil embedding, wire embedding and wire management. There are over 30 other comparable joint university-industry development projects.

A manufacturing institute case study: The IACMI

To get a better idea of what is evolving in the institutes, this section looks at a single institute in more depth. The IACMI is headquartered in Knoxville, Tennessee.[23] Its objective is to develop and demonstrate innovative technologies that will, within 10 years, make advanced fibre-reinforced polymer composites. Compared to existing techniques, it is intended to make such composites at 50% lower cost, using 75% less energy, and reusing or recycling more than 95% of the material.

Clear and unique institute focus. Institutes including IACMI are designed to address critical industry needs with a clear and unique focus. The objective IACMI is attempting to meet is the development of lightweight composites that offer significant benefits in energy efficiency and renewable power generation compared to current materials. This will require deployment of advanced technologies to make composites at a significantly lower cost, and more quickly, using less energy, and with the possibility of relatively easy recycling. Although there are numerous technical and institutional barriers, the field arguably offers significant opportunities for US industry.

Consortium approach. IACMI, like the other institutes, is based on a consortium across industry, universities and government. It includes large firms, such as Dow, Ford, General Electric, Dupont and Boeing, as well as smaller firms. A total of 57 firms are involved, reaching across the chemical, automotive and aerospace sectors. Overall, 15 universities, laboratories and colleges are involved, with university participants including the University of Tennessee, Pennsylvania State University, the University of Illinois, and Purdue University. State and other economic development entities are also engaged.

The core idea. The IACMI focus will be on dramatically lowering the overall manufacturing costs of advanced composites, cutting the energy required to form them and ensuring they are recyclable. It will create shared R&D and testing facilities and link leading industrial manufacturers, materials suppliers and university experts.

The industry value proposition. IACMI intends to offer four basic services to its industry partners:

- **Access to shared R&D resources.** Providing access to equipment, from laboratory level to full-scale production, to enable demonstration and testing and to reduce risk for industry investment.
- **Applied R&D.** Leveraging significant government R&D, plus cost sharing from industry, as well as academic investments, to create innovative solutions to challenges.
- **A composites virtual factory.** Giving access to end-to-end commercial modelling and simulation software for composites designers and manufacturers through a web-based platform.
- **Workforce training.** Providing specialised training to prepare the current and future workforce for the latest manufacturing methods and technologies for advanced composites.

Addressing goals and challenges. IACMI has developed five- and ten-year technical goals: to reach 25% then 50% lower-carbon fibre-reinforced polymer (CFRP) cost; to reach 50% then 75% reduction in CFRP embodied energy requirements; and to reach 80% then 95% composite recyclability into useful products. The institute's impact goals, with a series of targets to be achieved over time, include: enhanced energy productivity; reduced life-cycle energy consumption; increased domestic production capacity; job growth and economic development.

Roadmap and strategic investment plans. IACMI will take a portfolio approach to projects. Its initial projects were identified in a proposal to the US DoE. These include strengthening infrastructure capacity for materials and processing as well as modelling and simulation, and workforce development in strategic areas. The aim is national benefit, including in automotive, wind and compressed gas storage sectors.

A second phase involves technology roadmapping, which is driven by IACMI's Chief Technology Officer, and an industry and technology advisory board. This phase will identify key hurdles to manufacturing high-impact, large-scale advanced composites and prioritise opportunities across the materials and manufacturing supply chain.

A third area requires development of a strategic investment plan, which will be driven by IACMI's board and its technical advisory board. The aim will be to change the innovation cycle to enable rapid adoption and scale-up of advanced composites manufacturing. Ongoing open project calls for technology development projects will align with the strategic investment plan and technology roadmap, with an emphasis on projects with high near-term impact.

Accelerating discovery to application to production. This will be a general goal, and like other institutes, the IACMI will seek to:

- Establish a presence, at scale, in the "missing middle" of advanced manufacturing research (TRL 4-7).
- Create an industrial commons, supporting future manufacturing hubs, with active partnering between stakeholders.
- Emphasise and support longer-term investments by industry.
- Combine R&D with workforce development and training.

An overarching objective will be the creation of new US advanced manufacturing capabilities and industries in composite materials.

This review of the IACMI's structure and aims illustrates approaches being adopted by many of the new manufacturing institutes. However, the institute model is flexible, depending on the sector to be served, and can significantly vary.

Lessons learned by the manufacturing institutes

As has been mentioned earlier, the manufacturing institute programme was established very rapidly by the Obama administration at the president's personal direction in response to a policy crisis – a major decline in a key economic sector, manufacturing, in the aftermath of the 2008-09 recession. Because of Congressional deadlock, the administration was unable to start with a clean slate and design and implement a completely new programme. Instead it had to turn for funding and organisation to existing agencies with their existing programmes and funding, grafting new programmes onto established organisations. So the large foot of a new programme for manufacturing innovation had to be squeezed into existing agency programme shoes. Needless to say, it could not be a perfect fit.

Like any new programme, some of the experimental pilots will fail and some will succeed. Only a few of the new institutes have been around long enough to have their progress evaluated against their mission statements. The other institutes are still infants. Transforming a massive economic sector like manufacturing through innovation is not a short-term project. Clearly, there has been major progress in getting off the ground R&D and technology strategies in a range of new technology areas that could dramatically affect the future of manufacturing. One can now see a new set of lessons from various institutes as well as challenges that have come up as the institutes have evolved. These challenges, and a consideration of how to meet them, are set out below. Some institutes are already addressing many of these challenges, but others may now also need to address them. So the list below, developed from discussions with institute leaders, federal agency officials and participating university experts, represents early lessons learned which are starting to be applied to the evolving in-state network.

Orientation to technology versus production

The manufacturing institutes created to date are working in topic areas selected by the public R&D funding agencies. These topic areas reflect the agency missions, but not necessarily the priority needs of the particular manufacturing sector. Accordingly, the choice of topic areas has risked being more oriented to technology development as understood by agencies than by industry. This has tended to self-correct: agencies are increasingly soliciting industry perspectives.

To avoid these issues, the AMP2.0 report identified core criteria for selecting focus areas for advanced manufacturing institutes ("manufacturing technology areas" [MTAs]). While not formally applied by the agencies, these remain illuminating and relevant. The four criteria were:

- **Industry or market pull.** Does there exist a current "pull" or demand for this MTA by industry? If industry is not yet adopting this MTA, is there a strong perceived pull by the market or consumers?
- **Cross-cutting.** Does this MTA cut across many sectors (automotive, aerospace, biotech, infrastructure), and across multiple sizes of manufacturers in the supply chain network?

- **National or economic security.** Does failure to have US competence or dominance in this MTA pose a threat to national security or to economic security? Does lack of a US competence severely disadvantage US competitiveness in the supply network?
- **Leveraging US strengths.** Does this MTA leverage an already available workforce and education system, unique infrastructure, or policies? (PCAST, 2014).

If additional institutes are created, agencies could be encouraged to more formally weigh the AMP2.0 criteria in their topic selection process to ensure the match between industry and agency needs.

The limitation of federal support to five years

Starting with the announcement of the first manufacturing institute, America Makes, there has been a requirement that the institutes be self-sustaining (without federal funding) after five years. The Revitalise American Manufacturing Act, passed in 2014, likewise adopts a five-year term for federal support to manufacturing institutes created by NIST.

This approach follows the Sematech model, where DARPA's funding for the Sematech semiconductor industry consortium ended after five years. But, as discussed below, the institute idea itself derives from Germany's Fraunhofer Institutes, which face no such cut off of support after a short fixed term, from their federal government. The assumption that the institutes can become financially independent in five years is problematic. Reinvigorating manufacturing innovation is going to be a long term not a short-term project and requires realism about technology and business challenges.

Most of the technologies that the new institutes are being organised around will require a longer-term evolution than the five-year term currently fixed for federal support before they are ready for implementation at scale. Given the evolving development of the institutes, some mechanism for continued federal cost sharing will probably be required for a significant additional period beyond the initial five years. This could take the form of an evaluation process after five years with an opportunity for an institute to obtain a renewed term of funding if performance has been successful. Or, institutes, as they approach the end of their initial term, could compete for awards from an agency source of multi-year R&D federal funding, available to pursue technology development projects and, potentially, related training projects.

The research governance model

The manufacturing institutes were formed by federal mission agencies, and these carried over their regulatory and organisational perspectives as the institutes developed. Agencies have tended to treat and manage their institutes in ways they are familiar with, as research recipients. So the agency governance model is effectively an R&D supervisory model (through co-operative agreements), and agencies tend to see their role as research supervisors. Yet the role of the institutes is much broader. This role involves building lasting collaborations with support systems across a wide range of firms and researchers in many sectors, not only for research but also for testing, technology demonstration and feedback, product development, and workforce education and training.

The institutes' intended role is very complex and ambitious, and requires a different governance and support model than more straightforward research projects. To summarise, the governance system for federal research in many cases may not foster the

kind of collaboration required for the non-research aspects of the institutes' tasks, and may not prepare the institutes to be financially self-sustaining after five years. Thought needs to be given to how the governance model is working, including administrative delays in establishing new institutes. Should, for example, the cost-share funding from industry and states be controlled by the agency, or should the institutes set these parameters with the contributing stakeholders? Could the agencies shift from traditional research contract supervision and oversight to encourage a more collaborative model with growing state and local government, and especially industry, involvement?

Support from the network

The AMP2.0 report recommended that the growing group of manufacturing institutes be joined together into a supporting network. The report proposed, "a governance structure that maintains autonomy for individual institute operations while creating a public-private network governing council that oversees the broader performance of the network and the sustainability of the individual institutes." (PCAST, 2014). NIST is working to implement this recommendation, through the Manufacturing USA network. As NIST well understands, the network can serve a range of needs. As each new institute is established, it should not have to "reinvent the wheel." Many lessons have been learned about how to constitute governing boards and legal structures, how to manage intellectual property, how to set up tiers of participants, how to organise regional outreach and education efforts, and so forth. A strong, supportive network organisation could help ensure that common problems are shared by the institutes and tackled in common, and that best practices and lessons learned by individual institutes are studied and shared across the network.

Emphasis on R&D versus implementation

The AMP1.0 report envisioned institutes organised at TRL 4-7 ("Technology development" to "Technology demonstration" to "System and subsystem development") (PCAST, 2012). The supporting federal agencies have tended to organise the institutes around technology development for new technologies consistent with their missions, which is still some distance from industry implementation. This development focus may be inevitable given the gap in US R&D on manufacturing, but over time this will create an implementation gap in the role of the institutes. Without more process technologies, demonstration, testing and feedback systems, the institutes may limit their ability to bring in small and medium-sized manufacturing firms because sought-after technologies are not ready for these stages, where the smaller firms could pick them up. This will limit technology dissemination. Most institute leaders understand this well, but the issue continues to need focus.

In summary, the technology development role of the institutes is clearly important and central. However, the institutes need to be sure to build in the additional tasks required for TRL levels 5-7, further down the innovation pipeline, so the evolving technologies can be implemented, especially by smaller and medium-sized firms. The institutes are working to ensure this, but their evolving approaches need to be shared and compared.

Supply chain involvement

Institutes, as suggested above, have often focused initially on project calls for technology R&D that typically involve university and major firm researchers; smaller firms are usually not included because they have limited R&D capability. Yet the new technologies will not be adopted unless integrated supply chains including smaller firms

are brought in to understand and use them. For this to occur, the institutes will need to embrace more of a full supply chain approach, with supply chains engaged in technology demonstration, testing and training.

Workforce training and education

There is a similar potential problem for the role of the manufacturing institutes in workforce training and engineering education. Without engineering teams and a workforce skilled in the new technologies, in small as well as large firms, the evolving advanced manufacturing technologies simply cannot be widely implemented. Some institutes have seen that workforce training can be an early success for the institutes in serving their industrial constituents and sectors, and building networks of contacts with a wide range of firms. This is a particularly important way for the institutes to engage with both smaller firms and states, which play a role in workforce education through their community college systems. However, this has not always been the case. Agency contract and programme officers for the institutes tend to be technologists, not education experts, so many focus on the R&D side of the institute role. However, institutes need to master both sets of tasks to fully serve their industry sectors. The agencies should ensure a workforce education and training focus across the institutes. In fact, the evolving NNMI network could play a constructive role in introducing best education practices across the institutes.

The role of the states

From the outset, participants in the AMP1.0 and 2.0 processes, including government, industry and universities, saw a critical challenge of balance for the institutes. All manufacturing, in the end, is embedded in production and innovation ecosystems that are very regional. So the manufacturing institutes must keep one leg in regional manufacturing economies, which is where their industry and university constituencies are located. Yet the technologies the institutes are developing will also be needed nationally. 3D printing, for example, will not be just needed in northeast Ohio, it will be needed nationally and in many industrial sectors. Keeping one leg in regional economies and the other leg in the national economy creates a complicated, bifurcated model for the institutes.

Another issue some of the institutes are facing is that with a strong emphasis on R&D projects as their initial focus, they may be too tilted towards a national approach and need more balance. If federal support ends after a five-year term, the regional and local role the institutes can play becomes vital. Accordingly, support from states could be key to an institute's survival. If the institutes are not closely tied early on to regional economies, the support from states will simply not develop to the depth necessary. Some institutes are creating models for how to do this. LIFT, for example, has been particularly successful in bringing its participating states and their community colleges into the fold to build workforce education programmes, a state priority. IACMI has been effective in creating operating nodes supported in its participating states to more effectively involve them.

In summary, building state support by tying in to regional economies will be key for institute survival. For new government programmes to survive and thrive they not only need a strong substantive policy design, they must have a sound political support design that will sustain them. The political design is not easy: it must not distort the substantive policy design to serve political ends. Indeed, the political design must support the substantive policy design, but still build support to sustain it (Bonvillian, 2011). The

institutes need to find the right mix of political and substantive design. Developing a regional economic focus is not only important for the substantive model of a sustainable, viable institute, it is also important to the political aspect of future support.

An underlying problem: Historically insufficient federal R&D for advanced manufacturing

A significant issue that affects the ability to meet a number of challenges discussed above is the lack of past focus by federal R&D agencies on research on manufacturing. As discussed in earlier sections, successive federal governments in the United States assumed that manufacturing leadership was a given, and did not feel the need to make it a focus of R&D policy. That is part of the reason why the manufacturing institutes tend to focus more on earlier technology development stages rather than the additional focus on technology implementation as was proposed in the AMP report. And foundational research in manufacturing technologies is also still needed. If ongoing federal mission agency R&D can focus more on enabling technologies in manufacturing, that could be an important complement to the manufacturing institutes, helping to create new manufacturing technology paradigms. To be clear, ongoing federal research has supported major advances in such areas as digital and sensor technology, advanced materials, photonics, robotics, flexible electronics and composites. This has helped the technology community in the United States see that potential manufacturing paradigms are in sight, which is a major part of what makes this effort so interesting. However, without strong R&D input into the institutes, their technology development and implementation roles will lack a continuing foundation.

The government has taken important initial steps down this pathway of channeling research towards the institutes. In April 2016, the Subcommittee on Advanced Manufacturing (SAM) of the National Science and Technology Council (an arm of OSTP used for inter-agency collaborations) released a report entitled "Advanced Manufacturing: A Snapshot of Priority Technology Areas Across the Federal Government." (NTSC, 2016). While this effort has not linked the federal R&D portfolio to the institutes, it has at least identified many relevant ongoing R&D programmes that could be better linked. This task requires further attention.

Lessons from Fraunhofer

Finally, there are important lessons from Germany's Fraunhofer Organisation and Fraunhofer Institutes, which served as the model for the US institutes. Although the Fraunhofer Institutes have significant autonomy, the overall organisation allows participatory governance, as well as sharing of practices and research. The US institutes could benefit from a strong institute network, providing access to best practices and a shared governance model. With the development of the institute network, Manufacturing USA, in 2016, NIST began to pursue this task, asking the institute directors to take leadership. This could enable sharing of practices and collaborative programmes across institutes. The continuing central government support of Fraunhofer Institutes, which is not term-restricted as in the United States, has been critical for their sustainability and strength. Such central government support now needs to be considered in the United States.

In addition to a working network, the institutes need a continuous learning capability to stay ahead of issues, a role which the Fraunhofer system has performed, lately in co-ordination with larger government projects on "Industry 4.0". NIST and NSF have therefore also created a "think and do tank," MForesight – the Alliance for Manufacturing Foresight – to continuously evaluate technical and policy issues that the institutes face as a group. MForesight seeks to

provide "ideas and insights to business and government decision makers on emerging technology trends and opportunities for public-private investments in advanced manufacturing." (MForesight, 2017). Its portfolio of study projects also aims to promote technology innovation that can bridge the gap between research and manufacturers.

Conclusion

After a steep decline in its manufacturing sector in the decade of the 2000s, the United States is now playing manufacturing catch-up. As detailed above, the decline was characterised by a loss of 5.8 million manufacturing jobs, declining capital investment, declining output and, because of lower output, lower productivity than had been estimated previously. As economist David Autor and colleagues have delineated, the decline in manufacturing was also characterised by significant social disruption, through trade imbalances with China in manufactures.

If the United States is to compete with low-wage, low-cost competitors abroad, it must raise production efficiency to offset its higher costs, which means it must have a manufacturing innovation strategy. There are no real policy substitutes. Tax, trade and macroeconomic policy can improve the competitive position of US manufacturing at the margins but cannot significantly raise productivity and efficiency. Innovation in production technologies and processes, with accompanying business models to implement them, appear key.

The government began to focus on an innovation initiative for manufacturing in a 2011 PCAST report on "Ensuring American Leadership in Advanced Manufacturing". The policies were fleshed out in two PCAST reports in 2012 (on capturing domestic competitive advantage in advanced manufacturing; PCAST [2012]) and 2014 (on accelerating US advanced manufacturing"; PCAST [2014]), prepared by the president's Advanced Manufacturing Partnership, a collaboration between leading firms and universities. While the AMP proposed numerous approaches, the centrepiece was the advanced manufacturing institute concept, which the administration quickly acted on and began to implement well before the first AMP report was released in 2012.

The effort to establish a network of advanced manufacturing institutes got off to a promising start, attempting to address a critical gap in the US system for manufacturing innovation. It was a complex and challenging organisational model, requiring groups of firms, both small and large, as well as university researchers and states, to collaborate and cost share, under guidance from federal R&D agencies not used to managing such large teams.

The basic institute structure is now falling into place, and has focused initially on manufacturing technology development projects. However, an opportunity exists to consider a second stage of enhancements to the model. The institutes face a series of challenges, as described above, that can now be considered as they continue to scale up and mature. In particular, it would be desirable to:

- Improve the current research agency and institute governance model.
- Continue federal government support after the initial five-year commitment.
- Create a strong network of institutes where best practices in research and workforce education advances can be shared.
- Create an emphasis within the institutes on technology implementation at later TRLs as well as on technology development.

- Ensure that institutes emphasise (and collaborate) on optimal workforce training and education approaches.
- Ensure linkages between institutes and regional economies, in addition to serving manufacturing technology development at the national level.

In addition, federal R&D from mission agencies in the area of advanced manufacturing technologies could be better connected to the institutes. It would help, in particular, if these R&D funds were co-ordinated through common roadmaps with the institutes, so that the technologies do not get stranded but keep improving. Of course, the United States now has few options other than pursuing and upping its capabilities in advanced manufacturing, since its leading competitors are pursing somewhat similar strategies (see e.g. Forschungsunion and Acatech [2013], Kennedy [2015], Xinhua [2015], Xinhua [2016], Whang [2012], Manufacturing Technology Centre [2016], Catapult High Value Manufacturing Centres [2016] and Shipp [2012]).

The decline of manufacturing in the United States in the decade of the 2000s, has led to a new strategy for manufacturing based on innovation. This strategy for advanced manufacturing was recognised as one among a series of approaches needed to restore US production strength, from adjustments to tax, trade and macroeconomic policy, to new ways of providing training. But this new innovation policy was unlike anything that had been tried before by the United States in its manufacturing sector. The advanced manufacturing policy required a complex and challenging innovation organisation model, joining industries small and large, university research and federal and state government agencies in the common pursuit of new production technologies and processes. The policy sought a new competitive formula by raising production efficiency and productivity. The support for advanced manufacturing has been an attempt to apply an historic US economic strength – its innovation system – to an entirely new set of problems.

Notes

1. This chapter draws from the author's upcoming article in *Annals of Science and Technology* to be published in the first quarter of 2017, and will be elaborated on in an upcoming book on this subject with Peter L. Singer, to be published by MIT Press, planned for autumn 2017.
2. Bureau of Labor Statistics (BLS), Current Employment Statistics (CES) (manufacturing employment), *www.bls.gov/ces/*. See also the detailed review of manufacturing job loss in Atkinson et al. (2012) and Scott (2015).
3. Bureau of Labor Statistics (BLS), Current Employment Statistics (CES) (manufacturing employment), *www.bls.gov/ces/*.
4. Bureau of Economic Analysis (BEA), Fixed Assets Accounts (investments in private fixed assets by industry, *http://bea.gov*. See also Atkinson et al. (2012), pp. 47-58.
5. Bureau of Labor Statistics (BLS), Labor Productivity and Costs, Productivity change in the manufacturing sector (database), *www.bls.gov/lpc/prodybar.htm*.
6. Bureau of Economic Analysis (BEA), Foreign Trade, Exports, Imports and Balance of Goods by Selected NAICS-Based Product Code, Exhibit 1 in FT-900 Supplement for 12/15, 5 February 2016, *www.census.gov/foreign-trade/Press-Release/2015pr/12/ft900.pdf*.
7. Bureau of Economic Analysis (BEA), Trade in Goods with Advanced Technology Products, 2015, Exhibit 16, *www.census.gov/foreign-trade/balance/c0007.html*.
8. Bureau of Economic Analysis (BEA), US International Trade in Goods and Services, Exhibit 1, 5 February 2016, *www.census.gov/foreign-trade/Press-Release/2015pr/12/ft900.pdf*.
9. For a discussion of disruptive societal effects of US manufacturing decline, see Bonvillian (2016).

10. Bureau of Labor Statistics (BLS), Industries at a Glance, Manufacturing: NAICS 31-33, Workforce Statistics (July 2016), *www.bls.gov/iag/tgs/iag31-33.htm*.

11. The developments reviewed in this subsection, and sources discussing them, are detailed in, Bonvillian 2014.

12. This "industrial policy" concern remains embedded in partisan US politics. Although the manufacturing institutes created in the 2012-16 period, as discussed below, could be branded in this way, the crisis in manufacturing employment and plant closings tended to overcome such concerns, and bipartisan legislation supporting the institute model passed, as noted below, in 2014. In addition, the institutes are designed to be industry-led, industry cost-shared, and collaborative, not government-dominated.

13. In this period there were a number of significant articles on the predicament of US manufacturing that provided a foundation for the studies reviewed below, although the MIT study discussed below was the most extensive. These other articles included: Tassey (2010); Fuchs and Kirchain (2010); Houseman et al. (2011); Breznitz and Cowhey (2012); Atkinson et al. (2012); Helper, Kruger and Wial (2012); Shipp et al. (2012); Bonvillian (2012); and Pisano and Shih (2012).

14. Names of AMP1.0 Steering Committee members from companies and universities can be found in, The White House, Office of the Press Secretary, Press Release, "Report to President Outlines Approaches to Spur Domestic Manufacturing Investment and Innovation", 12 July 2012, *www.whitehouse.gov/the-press-office/2012/07/17/report-president-outlines-approaches-spur-domestic-manufacturing-investm*.

15. In the US, both the US Department of Defense (US DoD) and the National Aeronautics and Space Administration (NASA) have developed similar but somewhat different TRLs. The AMP applied the US DoD terminology.

16. See also the statement on the PIE website, *http://web.mit.edu/pie/research/index.html*.

17. See e.g. Deloitte and the Manufacturing Institute (2011). This work found that 82% of senior executives in manufacturing reported moderate to serious gaps in the availability of qualified, skilled candidates. 74% of manufacturers reported that these shortages affected their ability to expand operations.

18. See S.1468, 113th Congress, 2nd Session, *www.govtrack.us/congress/bills/113/s1468/text*; HR 2996, Revitalize American Manufacturing and Innovation, 113th Congress, 2nd Session, Congress.gov, bill actions, *www.congress.gov/bill/113th-congress/house-bill/2996/actions*.

19. Sematech was a consortium of semiconductor fabricators and equipment makers that in the 1990s was facing imminent demise from strong competitors in Japan. Industry funding was matched by the Defense Advanced Research Projects Agency (DARPA). The consortium focused on major efficiency and quality improvements in semiconductor manufacturing; after five years production leadership was restored and DARPA funding ended. Sematech continued as a key technology planning organisation to keep the industry on a Moore's Law roadmap.

20. Aside from Mantech, DARPA's Deputy Director was involved in the AMP1.0 effort, and DARPA led a sizeable portfolio of DARPA advanced manufacturing R&D and advised on the AMP reports.

21. Descriptions of the institutes draw from each of their websites. Descriptions of the manufacturing technologies they aim to advance are drawn from NTSC (2016), pp. 36-39.

22. Information in this section is drawn from the America Makes website, *www.americamakes.us/*.

23. This section is drawn from NIST (2016).

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ANNEX 11.A.1

Description of the advanced manufacturing institutes

This annex describes 13 advanced manufacturing institutes other than America Makes, which were not described in the main body of this chapter:

The **Digital Manufacturing and Design Innovation Institute (DMDII)** was formed in 2014 with a hub located in Chicago. Digital manufacturing involves the use of integrated computer-based systems, including simulation, three-dimensional visualisation, analytics and collaboration tools, to create simultaneous product and manufacturing process definitions. Design innovation is the ability to apply these technologies, tools, and products to reimagine the entire manufacturing process from end-to-end.

DMDII has 201 members, including major firms from a wide range of sectors, numerous smaller firms and 11 universities. Its USD 70 million in US DoD Army Mantech funding was matched with industry and state funding of USD 248 million. DMDII's mission is digital manufacturing to lower product design costs by fostering deep connections between suppliers. It also aims to lower production costs and reduce capital requirements, through better linkages from end-to-end of the product life cycle. Cutting time to market through faster iterations, developing and implementing innovations in digital design, digital factories and digital supply chains are also goals. Overall, it seeks to develop both new products and improve legacy products.

Lightweight Innovations for Tomorrow (LIFT) addresses lightweight and modern metals, was founded in 2014. Its hub is in Detroit, Michigan, supplemented with locations in Michigan, Ohio, Indiana, Tennessee and Kentucky. Lightweight and advanced metals offer major performance enhancements and greater energy efficiency that can improve the performance of many systems in defence, energy, transportation and general engineered products. Lightweight metals have applications in wind turbines, medical technology, pressure vessels, and alternative energy sources.

LIFT has 78 members, from a wide range of firms, small and large, including metals and aerospace firms and automotive suppliers, and 17 universities, which matched USD 70 million in federal funds from the Navy Mantech programme and the Office of Naval Research. LIFT's mission is to innovate in lightweight high-performing metals production and enable the resulting technologies to be applied across industries. LIFT is working on projects in melting, thermo-mechanical processes, powder processing, agile low-cost tooling, coatings, and joining, with widespread applications in automotive, aerospace, ship building, railroads, fabrication and other sectors.

Power America – for next-generation power electronics was created in 2015 to develop wide bandgap semiconductor technology. This could enable a major increase in the energy efficiency and reliability of power electronics through smaller, faster and more efficient semiconductor materials. These non-silicon-based technologies are able to operate at higher temperatures, can block higher voltages, switch faster with less power loss, are potentially more reliable and carry substantial system-level benefits. These capabilities make it possible to reduce weight, volume, and life-cycle costs in a wide range of power applications. Such semiconductor technology will have many uses, including in industrial motor systems, consumer electronics and data centres, and in conversion of renewable energy sources (solar and wind). If widespread adoption of these technologies could be accomplished in even a few applications, then very significant electrical power savings, including in industrial production, could be achieved. The higher cost of wide bandgap technologies is expected to decline as higher production levels are achieved.

Supported by the Department of Energy's Energy Efficiency and Renewable Energy Advanced Manufacturing office, Power America includes over 20 industry partners, over 10 universities and three laboratories, and is based in Raleigh, North Carolina.

The **Institute for Advanced Composites Manufacturing Innovation (IACMI)** was formed in 2015 to develop and demonstrate technologies that will make advanced fibre-reinforced polymer composites at 50% lower cost, using 75% less energy, with 95% or more reuse or recycling of material within a decade. The IACMI is headquartered in Knoxville, Tennessee.

Lightweight, high-strength, and high-stiffness composite materials have been identified as a key technology that can cut across industrial sectors, with the potential to achieve a more energy-efficient transportation sector, enable efficient power generation, and increase renewable power production. The range of lightweight, high-strength composite applications is vast, from autos, to aircraft, to wind blades. The challenges include high costs, low production speeds (long cycle times), high manufacturing energy intensity for composite materials, recyclability, and a need to improve design, modelling and inspection tools and meet regulatory requirements. Technology acceleration and manufacturing research is needed to meet production cost and performance targets, from constituent materials production to final composite structure fabrication.

The IACMI was supported by a USD 70 million award from the Department of Energy's Energy Efficiency and Renewable Energy Advanced Manufacturing office, which was matched by USD 180 million. The IACMI includes 57 companies, 15 universities and laboratories and 14 other kinds of entities.

The **American Institute for Manufacturing Integrated Photonics (AIM Photonics)** was formed in 2015 with hub locations in Albany and Rochester, New York. Its goal is to foster ultra-high-speed transmission of signals for communications, new high-performance computing and sensors, and imaging for health sector advances.

Integrated photonics requires the integration of multiple photonic and electronic devices (e.g. lasers, detectors, waveguides and passive structures, modulators, electronic controls, and optical interconnects) on a single substrate with nanoscale features. The benefits of integrating these components could be very significant: simplified system design, improved system performance, reduced component space and power consumption, and improved performance and reliability, which will enable important new capabilities and functionality with lower costs. The current photonics manufacturing sector is a collection of interrelated but largely independent businesses, organisations and activities. The sector is a

potential ecosystem, but lacks the organisation and aggregated market strength needed to efficiently innovate manufacturing technologies for cost-effective design, fabrication, testing, assembly, and packaging of integrated photonic devices.

AIM Photonics is to focus on building an end-to-end photonics ecosystem, including domestic foundries, integrated design tools, and automated production packaging, assembly and testing, as well as workforce development. The federal award was matched by over USD 200 million in state and industry support.

Flexible Hybrid Electronics (NextFlex) was formed in 2015 with a hub in San Jose, in Silicon Valley. Its goal is to produce highly tailorable devices on flexible, stretchable substrates that combine thin complementary metal oxide semiconductor technology for constructing integrated circuits components with new components added through printing processes. These represent flexible and hybrid features for circuits, communications, sensing and power sources that are unlike current silicon processors.

Flexible hybrid electronics would preserve the full operation of traditional electronic circuits, but in novel flexible architectures that could be part of curved, irregular and stretched objects. They could expand traditional electronic packaging to new forms, enabling new commercial and defence technologies. Examples include medical devices, prosthetics and sensors, sensors to monitor structural or vehicle performance, sensors interoperating through the Internet or as sensor clusters to monitor physical positions, wearable performance or information devices, human-robotic interface devices, and lightweight human-portable electronic systems.

The US DoD Mantech award was for USD 75 million, with an industry and state and local government cost share of USD 96 million. NextFlex includes 39 member companies ranging from semiconductor firms and their suppliers, to companies in aerospace and the life sciences. Also included are over 30 universities, and state and regional organisations.

Advanced Functional Fabrics of America (AFFOA) was launched in April 2016 and commenced its start-up period, with over 80 members, as of the end of 2016. The institute is headquartered in Massachusetts, and plans a series of regional nodes.

Scientific advances have enabled fibres and textiles with extraordinary properties including increased strength, flame resistance, and electrical conductivity. Such fibres could become electronic, sensor and communications components. This new range of fibres and textiles are composed of speciality fabrics, industrial fabrics, electronic textiles, and other forms of advanced textiles. They could provide communication, lighting, cooling, health monitoring, battery storage and many more new functions. These technical textiles are built on a foundation of synthetic, natural fibre blends and multi-material fibres that have a wide range of applications, in commercial and defence sectors, which go far beyond traditional wearable fabrics.

AFFOA headquarters are in Cambridge, Massachusetts, and it combines USD 75 million in US DoD Mantech funds with some USD 240 million in industry and state support. AFFOA aims to serve as a public-private partnership to support an end-to-end innovation ecosystem in the United States for revolutionary fibres and textiles manufacturing. The institute also aims to use domestic manufacturing facilities to develop and scale up manufacturing processes. It plans to provide rapid product realisation opportunities, based on design and simulation tools, pilot production facilities, a collaborative infrastructure for suppliers, and workforce development opportunities. The institute wants to effect a revolution in fibre and textiles, incorporating IT advances and integrating intelligent devices with fibres.

The **Smart Manufacturing Innovation Institute** was announced in June 2016 and is now in its start-up phase and is setting membership (The White House, 2016). The institute is headquartered in Los Angeles.

Smart manufacturing can be characterised as the convergence of information and communications technologies with manufacturing processes, to allow a new level of real-time control of energy, productivity, and costs across factories and companies. Smart manufacturing was identified by the AMP2.0 report as a high-priority manufacturing technology area in need of federal investment. Being able to combine advanced sensors, controls, information technology processes and platforms, and advanced energy and production management systems, smart manufacturing has the potential to increase energy efficiency and manufacturing capability in a wide range of industrial sectors.

Of the USD 140 million Smart Manufacturing Innovation Institute budget, USD 70 million over five years is already appropriated federal funding from the Energy Department's Advanced Manufacturing Office. The remainder is in matching funds. The Smart Manufacturing Innovation Institute will focus on integrating information technology in the manufacturing process through devices like smart sensors that reduce energy use. For example, the institute plans to partner with the US DoE's Institute for Advanced Composites Manufacturing Innovation to test advanced sensors in the production of carbon fibre. The Smart Manufacturing Innovation Institute expects to partner with more than 200 companies, universities, national laboratories and non-profits. Microsoft Corp., Alcoa Inc., Corning Inc., ExxonMobil, Google, the National Renewable Energy Laboratory and numerous smaller firms are among the Smart Manufacturing Innovation Institute partners. The institute plans to launch five centres, focusing on technology development and transfer and workforce training, in regions around the country, headed by universities and laboratories in California (UCLA), Texas (Texas A&M), North Carolina (NC State University), New York (Rensselaer Polytechnic Institute), and Washington (Pacific Northwest National Laboratory).

The **Rapid Advancement in Process Intensification Deployment Institute (RAPID):** on 9 December 2016, the EERE office announced that a consortium led by the American Institute of Chemical Engineers would form the fourth institute sponsored by the Department of Energy, calling it a critical step in the administration's effort to double US energy productivity by 2030. Leveraging up to USD 70 million in federal funding with a higher level of private cost-share commitments from over 130 partners, RAPID will focus on developing breakthrough technologies to boost domestic energy productivity and energy efficiency by 20% in five years through manufacturing processes in industries such as oil and gas, pulp and paper and various domestic chemical manufacturers.

Traditional chemical manufacturing relies on large-scale, energy-intensive processing. The new institute will leverage approaches to modular chemical process intensification – including combining multiple, complex processes such as mixing, reaction, and separation into single steps – with the goal of improving energy productivity and efficiency, cutting operating costs and reducing waste. Process breakthroughs can dramatically shrink the footprint of equipment needed on a factory floor or eliminate waste by using the raw input materials more efficiently. For example, by simplifying and shrinking the process, this approach could enable natural gas refining directly at the wellhead, saving up to half of the energy lost in the ethanol cracking process today. In the chemical industry alone, these technologies could save more than USD 9 billion annually in US processing costs.

The **National Institute for Innovation in Manufacturing Biopharmaceuticals (NIIMBL):** on 16 December 2016, Secretary of Commerce Penny Pritzker announced an

award of USD 70 million to the new NIIMBL institute. This is the first institute with a focus area proposed by industry and the first funded by the Department of Commerce. The agency developed an "open topic" approach, where a new institute could cover any area not currently targeted by an existing institute. NIST had launched an "industry-proposed institutes competition" as a way to allow a bottom-up topic selection process to allow industry-led consortia to propose technology areas seen as critical by regional manufacturers. NIIMBL was the result.

NIIMBL will aim to transform the production process for biopharmaceutical products. Overall, it will seek to advance US leadership in the biopharmaceutical industry, improve medical treatments and ensure a qualified workforce by developing new training programmes matched to specific biopharmaceutical skill needs. The announcement was made at the University of Delaware, which will co-ordinate the institute in partnership with the Department of Commerce's NIST. In addition to the federal funding, the new institute is matched by an initial private investment of USD 129 million from a consortium of 150 companies, educational institutions, research centres, co-ordinating bodies, non-profits and manufacturing extension partnerships across the country.

The **Advanced Regenerative Manufacturing Institute (ARMI):** on 21 December 2016, the Department of Defense announced an award to establish ARMI at a White House event celebrating the progress the National Network for Manufacturing Innovation, now Manufacturing USA, has made. This new institute was the seventh led by the US DoD.

New Hampshire's US senators and its governor joined in a parallel, in-state, bipartisan announcement of the USD 80 million, five-year award to establish the biomanufacturing consortium, which will be headquartered in the Manchester Millyard. The institute – led by a coalition that includes DEKA R&D Corporation, the University of New Hampshire and Dartmouth-Hitchcock health care system – is tasked with developing and biomanufacturing tissues and organs that can be transplanted into patients. DEKA founder Dean Kamen will direct the institute. It would pioneer next-generation manufacturing techniques for repairing and replacing cells and tissues. If successful, such technology could lead to the ability to manufacture new skin or life-saving organs for the many Americans stuck on transplant waiting lists. The institute will focus on solving the cross-cutting manufacturing challenges that stand in the way of producing new synthetic tissues and organs, such as improving the availability, reproducibility, accessibility, and standardisation of manufacturing materials, technologies and processes. Collaborations are expected across multiple disciplines, from 3D bioprinting, cell science and process design, to automated pharmaceutical screening methods, to the supply chain expertise needed to rapidly produce and transport these life-saving materials.

Reducing Embodied Energy and Decreasing Emissions (REMADE) in Materials Manufacturing, formed by the US DoE, was selected on 4 January 2017, to be headquartered in Rochester, New York and led by the Sustainable Manufacturing Innovation Alliance. REMADE will leverage up to USD 70 million in federal funding, subject to appropriations, and will be matched by USD 70 million in private cost-share commitments from over 100 partners. REMADE will focus on driving down the cost of technologies needed to reuse, recycle and remanufacture materials such as metals, fibres, polymers and electronic waste and aims to achieve a 50% improvement in overall energy efficiency by 2027. These efficiency measures, the US DoE indicated, could save billions in energy costs and improve US economic competitiveness through innovative new manufacturing techniques.

It would aim to reduce the total lifetime energy use of manufactured materials via reuse and recycling. The institute will focus on reducing the total lifetime use of energy in manufactured materials by developing new cradle-to-cradle technologies for the reuse, recycling, and remanufacturing of manmade materials. US manufacturing consumes nearly one-third of the nation's total energy use annually, with much of that energy embodied in the physical products made in manufacturing. New technologies to better repurpose these materials could save US manufacturers and the nation up to 1.6 quadrillion British thermal units of energy annually, equivalent to 280 million barrels of oil, or a month's worth of oil imports.

The US DoD proposed the **Advanced Robotics Manufacturing Institute (ARM)** to focus on building US leadership in smart collaborative robotics, where advanced robots work alongside humans seamlessly, safely, and intuitively to do the heavy lifting on an assembly line or handle with precision intricate or dangerous tasks. The US DoD indicated assistive robotics has the potential to change a broad swath of manufacturing sectors, from defence and space to automotive and health sectors, enabling the reliable and efficient production of high-quality, customised products.

ARM, the 14th and last Manufacturing USA Institute to be announced by the Obama administration was named on 13 January 2017. It will be headquartered in Pittsburgh, and the proposal group was convened by Carnegie Mellon University. The institute will bring together a very large team, including 84 industry partners, 35 universities and 40 other groups in 31 states. Federal funds plus industry and state cost sharing will total some USD 250 million; the federal commitment is for USD 80 million. Clemson University's Center for Workforce Development will lead the new institute's workforce training programmes.

The US DoD described in its announcement statement the need for the new institute:

"The use of robotics is already present in manufacturing environments, but today's robots are typically expensive, singularly purposed, challenging to reprogram, and require isolation from humans for safety. Robotics are increasingly necessary to achieve the level of precision required for defense and other industrial manufacturing needs, but the capital cost and complexity of use often limits small to mid-size manufacturers from utilizing the technology. The ARM Institute's mission therefore is to create and then deploy robotic technology by integrating the diverse collection of industry practices and institutional knowledge across many disciplines – sensor technologies, end-effector development, software and artificial intelligence, materials science, human and machine behavior modeling, and quality assurance – to realize the promises of a robust manufacturing innovation ecosystem. Technologies ripe for significant evolution within the ARM Institute include, but are not limited to, collaborative robotics, robot control (learning, adaptation, and repurposing), dexterous manipulation, autonomous navigation and mobility, perception and sensing, and testing, verification, and validation." (US DoD, 2017).

The US DoD characterised the current domestic capabilities in manufacturing robotics technology as "fragmented," citing a need for better organisation and collaboration to better position the United States for the global competition in this sector.

An additional Department of Commerce institute, bringing the total to 15, could be developed since NIST's topic selection process had been completed, but the final selection process was subject to the availability of 2017 funds.

The institutes have already been hard at work. The administration has proffered a series of examples on what the institutes have been accomplishing (The White House, 2016):

- To help anchor production of new semiconductor technologies in the United States and accelerate the commercialisation of advanced power electronics, in March, the Power America Manufacturing Innovation Institute successfully partnered with X-FAB in Lubbock, TX, to upgrade a USD 100 million foundry to produce cost-competitive, next-generation wide bandgap semiconductors, enabling new business opportunities to sustain hundreds of jobs.
- Using next-generation metals manufacturing techniques, Lightweight Innovations for Tomorrow (LIFT), the Detroit institute focused on lightweight metals, has successfully demonstrated how to reduce the weight of core metal parts found in cars and trucks. A reduction of 40% has been achieved, potentially improving fuel efficiency and saving on fuel costs. In addition, LIFT has introduced curriculum in 22 states to train workers on the use of lightweight metals. In the summer of 2016, 38 companies hosted students in paid manufacturing internships, in partnership with LIFT.
- America Makes has attracted hundreds of millions of dollars in new manufacturing investment to its region. This has included helping to attract General Electric's new USD 32 million global 3D printing hub and spurring Alcoa to invest USD 60 million in its New Kensington, Pa. facilities. Both of these investments will benefit from proximity to America Makes and its expertise in 3D printing with metal powders.
- In addition, America Makes, with Deloitte and other partners, has created a free online course on the fundamentals of 3D printing for businesses. Over the last year, over 14 000 business leaders have taken this course to learn what 3D printing can do for their businesses.

Deloitte, commissioned by DoD Mantech, undertook an independent assessment of the institute model in 2016. Its overall findings, released in a January 2017 report, were quite positive (Deloitte, Manufacturing USA, A Third-Party Evaluation of Program Design and Progress, Washington, DC). It found that adoption of advanced manufacturing was critical for progress in the overall domestic economy to improve productivity growth and the trade imbalance, and for job creation. In this regard, the review found that the public-private partnership model of the institutes can create collaborations to improve R&D investment in manufacturing, overcome problems of collective action in the sector, reduce barriers to innovation, enable better access to intellectual property, and cut risk and cost through shared asset access. Concerning technology facilitation, the review found that institutes can play a significant role in de-risking investments in manufacturing R&D, particularly given the pattern of uneven investment between firms of different sizes and in different sectors. Shared advanced equipment, R&D pooling, technology roadmapping and knowledge-sharing enabled by the institutes could create significant benefits for industry participants who would be unable to achieve them on their own.

Regarding workforce training, Deloitte found that the institute model could mitigate the talent gap industrial firms now face as they move into advanced manufacturing. Institute workforce programmes included assessments of workforce supply and demand, employee credentialing and certification, and technology-focused training and apprenticeship programmes. It also found significant progress in creating improved ecosystems for production. The portfolio of institutes, both in the range of technology focus areas and geographical reach, was a strength of the system. Their high levels of membership from

different sizes and types of firms was a signal of the initial success of the model. The institutes were also found to be playing a role in strengthening regional economic clusters key to regional growth. The Deloitte report also made a number of programme recommendations, some of which complement the list of institute challenges that appears in this chapter. Overall, the Deloitte review amounted to an early certification from an independent expert source that the institute model was on the right track.

The Next Production Revolution
Implications for Governments and Business
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PART II

Chapter 12

China and the next production revolution

by
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The People's Republic of China (hereafter "China") is the largest contributor to global value-added in manufacturing. In recent years many Chinese companies have made great progress in creating and using new production technologies. For example, China is now the world's largest user of industrial robots. These developments have been accompanied by a series of major policy initiatives and related public investments, an overarching aim of which is to advance the use of digital technologies in manufacturing. China's goal of increasing the knowledge content of domestic production will expand the range of markets in which China competes. But upgrading manufacturing in China faces complex challenges. Technological capabilities remain highly uneven across the business sector. Challenges exist not only in increasing government investment in science and innovation, but also in commercialising research, improving infrastructures, making markets work more efficiently, and encouraging private sector innovation. Policy also needs to cope with a range of related developments, such as labour-market disruption, the growing importance of cyber security and the need for improved policy co-ordination.

The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Introduction

This chapter examines the development and use of a set of new and emerging technologies in manufacturing in the People's Republic of China (hereafter "China"). The focus is on five technologies: information and communication technologies (ICTs), industrial robotics, 3D printing, biotechnology and nanotechnology. These technologies are central to what is here termed the "next production revolution". As well as reviewing the development and use of these technologies, the chapter examines recent government initiatives to facilitate upgraded manufacturing, such as "Made in China 2025" and "Internet Plus". Also described are public policies towards each of the technologies in question. The description of these policies is juxtaposed with recent OECD technology-specific policy suggestions. The final section of this chapter examines key challenges for Chinese businesses and policymakers in upgrading manufacturing.

This chapter shows that in recent years many Chinese companies have made great strides in creating and using new production technologies. China is now the world's largest user of industrial robots, and the world's largest market for machine-to-machine services. By April 2015, China ranked third in the global number of 3D printing patents. And by 2010 China ranked first in the number of Science Citation Index publications in nanotechnology. Such developments have been accompanied by extraordinarily broad and ambitious government initiatives and investments, the overarching aim of which is to achieve excellence in applying digital technologies in manufacturing.

While progress has been rapid, upgrading in manufacturing faces complex challenges. For example, technological capabilities in the business sector remain highly uneven. Challenges exist not only in increasing government investment in science, research and innovation, but also in commercialising research, improving infrastructures, making markets work more efficiently, and encouraging private sector innovation. While many policies promote the technologies necessary to upgrade manufacturing, policy also needs to cope with a range of related developments, such as labour-market disruption and the growing importance of cyber security. At the same time, attention must be given to issues of governance, as it relates e.g. to co-ordination between government departments, as well as between central and regional public bodies.

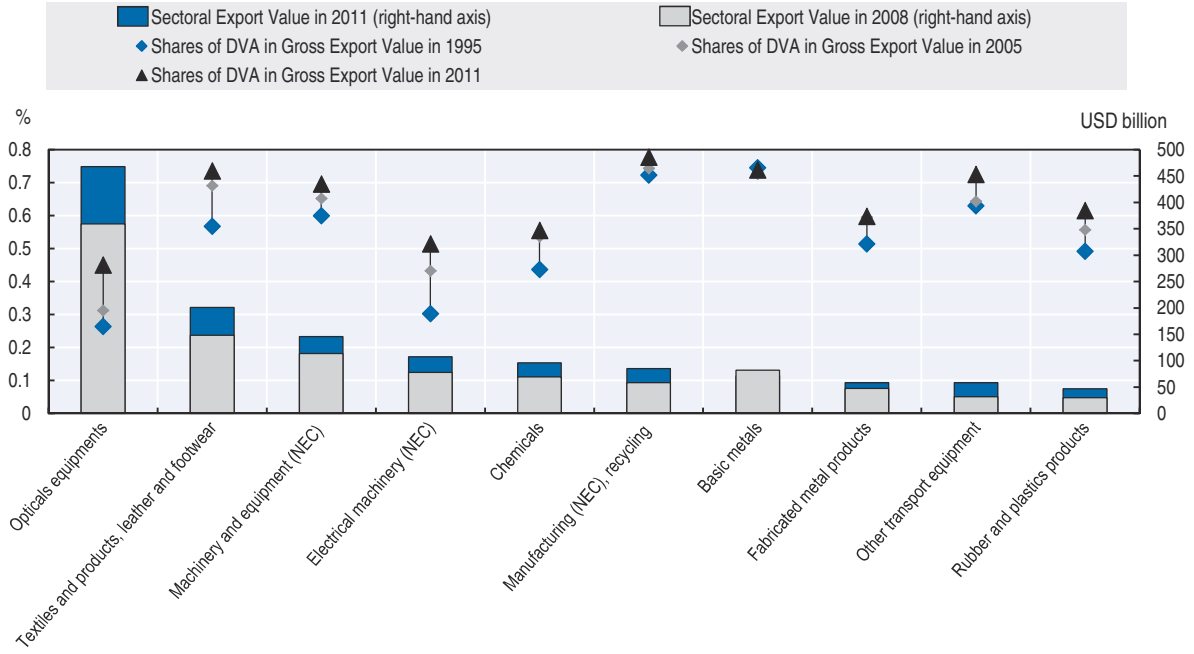
Chinese manufacturing: Key technologies and recent developments

This section considers progress in Chinese manufacturing in developing and using a variety of digital technologies, robotics, 3D printing, biotechnology, nanotechnology and new materials. For each of these technologies, the text describes the OECD's suggestions as to what good policy requires. The text then outlines the policy measures being adopted in China. Gaps in the Chinese policy offering are identified in a number of places. Measures adopted in OECD countries are also referenced, for comparative purposes.

China's weight in global manufacturing has many implications for itself and for production elsewhere in the world. Manufacturing is a foundation of China's economy. In

2014, manufacturing in China accounted for 19% of global manufacturing value-added and 35.9% of China's gross domestic product (GDP) (Chinese Academy of Engineering, 2015), leading the world for the fifth consecutive year. Furthermore, across China's main export sectors, recent decades have seen an increase in domestic value-added in gross exports (Figure 12.1). The Chinese premier recently stressed that upgrading traditional and new sectors of manufacturing is essential for China's long-term development (Li K., 2015).

Figure 12.1. **Change in sectoral export value and shares of domestic value-added in gross export value**



NEC = not elsewhere classified.
Source: OECD (2017e), TiVA database, *https://stats.oecd.org/index.aspx?queryid=66237* (accessed January 2017).

StatLink http://dx.doi.org/10.1787/888933473884

Under the government's innovation-driven development strategy, China is also trying to gain ground in high-tech manufacturing. Manned space flights, manned deep-sea submersibles, high-speed rail and the world's fastest supercomputer are all examples of China's manufacturing-related achievements. Furthermore, these achievements are associated with progress in research, education and infrastructure (Ministry of Industry and Information Technology, 2015c). China's gross expenditure on research and development was slightly over 2% of GDP in 2014, surpassing that of the European Union and well above countries with a similar level of GDP per capita (OECD, 2017a). And in 2014, manufacturing-led invention patent applications in China (Figure 12.2).

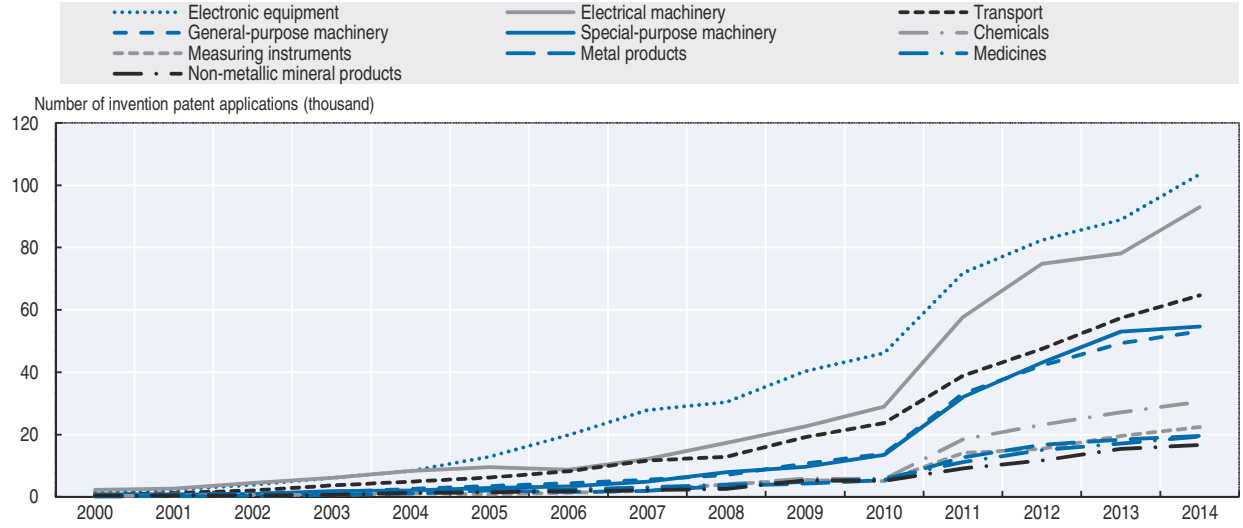
China's goal of increasing the knowledge content of domestic production will expand the range of markets in which China competes and contributes to the development of production technologies in those markets. Among 25 economies in a recent study, China's share of high-tech exports increased from 6% in 2000 to 37% in 2013, and it is now the largest exporter of high-tech goods (HSBC, 2014).

But manufacturing in China also faces multiple challenges. Much of China's manufacturing industry does not use state-of-the-art technology (Figure 12.3), and while China's labour productivity has risen over the past decade, it is still much lower than in the

United States (and other developed countries) (OECD, 2015a). The competitiveness of China in global value chains (GVCs) is still concentrated in processing and assembly (OECD, 2013), based in many instances on low-cost labour and raw materials. However, salaries for employees in manufacturing in 2014 had increased by 66%, relative to 2010. This exceeded the economy-wide average increase of 54% (National Bureau of Statistics of China, 2014). Product quality and brand awareness are still lacking for "Made in China". New demands for greener manufacturing have arisen, as air, water and soil pollution from industrial production have worsened. And in spite of significantly increased research and development (R&D), China still relies heavily on imports for advanced manufacturing. In 2013, imported semiconductors exceeded oil as China's largest import item (Ministry of Industry and Information Technology, 2015c).

Figure 12.2. **Change in invention patent applications, 2000-14**

Top ten sectors with most invention patent applications in 2014



Notes: Time series data by industrial sector in China are only available for enterprises above a certain turnover. But not all qualified enterprises are required to report their data. Furthermore, there have been several changes which reduce the consistency of the time series. For the period covered by this figure there have been three major adjustments: i) 2000-06, the reporting enterprises include non-state-owned enterprises (SOEs) with more than CNY 5 million turnover and all SOEs; ii) 2007-10, the reporting enterprises are those with more than CNY 5 million turnover; and iii) 2011-14, the reporting enterprises are those with a turnover of more than CNY 20 million. The number of reporting enterprises greatly increased from 41 002 in 2010 to 301 630 in 2011 after the adjustment of methodology in 2010, which explains the obvious uptick shown since 2010.

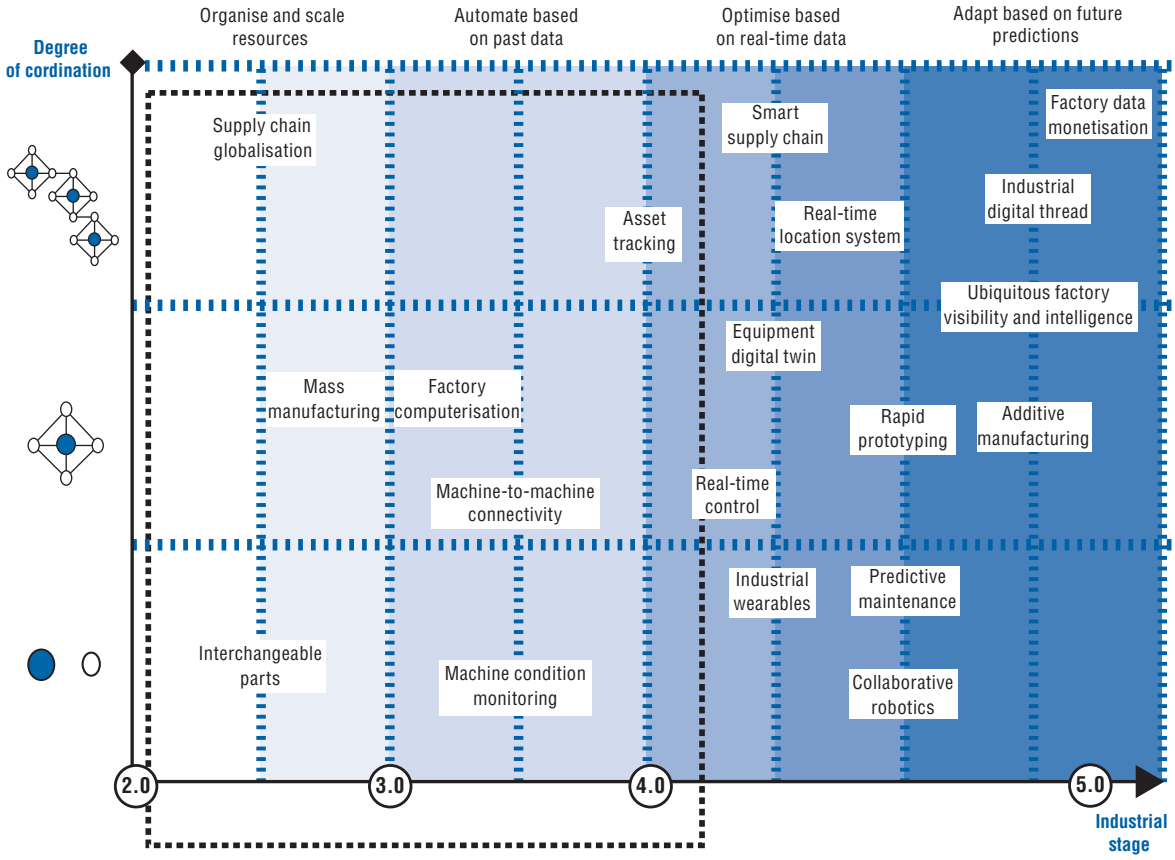
Sources: National Bureau of Statistics of China (2015), *China Statistics on Science and Technology Activities of Industrial Enterprises*.

StatLink http://dx.doi.org/10.1787/888933473899

Sizeable parts of Chinese manufacturing experience shortcomings in management and digital capability. The private sector's role in some areas of R&D is also limited, due to lack of resources or proper incentives. Technological change is also raising demand for skilled managers, researchers and technicians, which is not easily met. Information security is also a growing concern. Meanwhile, global competition has intensified as advanced manufacturing becomes a strategic priority for many developed countries, and some multinational firms are moving high-end manufacturing back home.

China is following a two-pronged approach to manufacturing. Chinese manufacturers are, on the one hand, aiming to maintain competiveness in traditional fields, such as processing and assembly, by increasing efficiency and product quality and reducing costs. On the other hand, many manufacturers are also engaged in product innovation in the

Figure 12.3. **Progression in the use of different types of ICT by stage of industrial development**



Notes: The symbols next to the vertical axis indicate the degree of co-ordination. Most Chinese factories operate with Industry 2.0-3.0.
Source: STM Stieler and IoT ONE (2016), "Growing from big to strong", *www.stm-stieler.de/files/558:A_Pragmatic_Assessment_of_Chinese_Industrial_Automation_2016_08_22.pdf*.

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hope of seizing opportunities in new sectors. Against this background, as discussed below, enabling technologies are being more widely adopted in industry.

Digital technologies

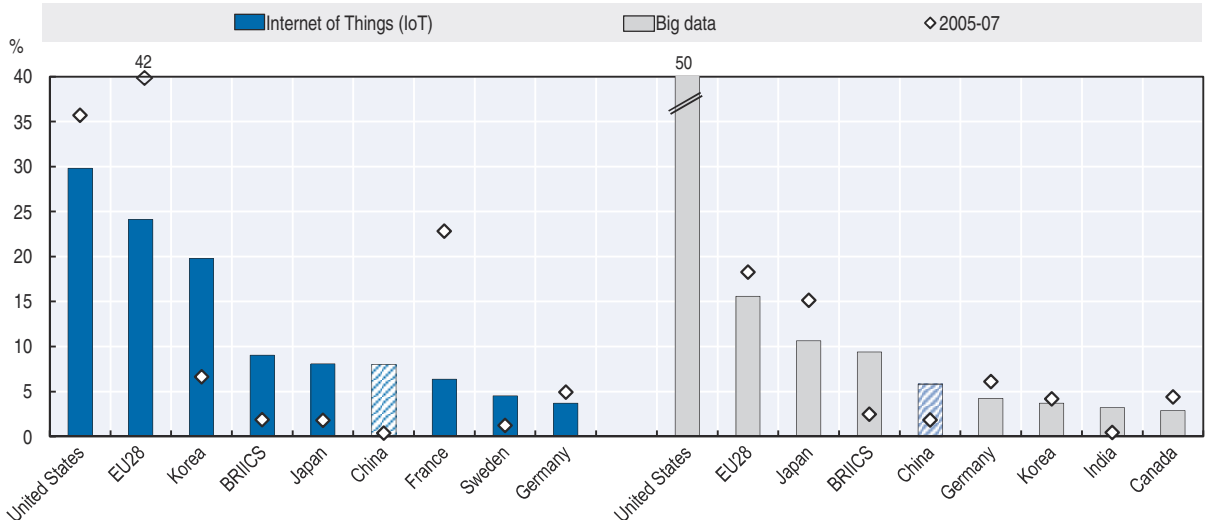
The importance of ICTs – such as the Internet of Things (IoT), cloud computing and big data – is recognised by leading figures in Chinese industry. Jack Ma, founder and executive chairman of the Alibaba Group, which owns many highly successful Internet-based brands in China, asserted that "The most important source of energy for future manufacturing is not oil, but data" (Li Q., 2015). ICTs are being employed across manufacturing processes, from logistics to production, management and services.

In 2014, the IoT market in China reached over CNY 600 billion (USD 94 billion), growing at a compound annual rate of over 30% since 2011.[1] China is expected to become one of the leading markets globally, with nearly one out of every five industrial units (e.g. machines, tools and components) connected by 2020 (IDC, 2015). In 2014, the market for public cloud services reached CNY 7.02 billion (around USD 1.1 billion), growing by 47.5% with respect to 2013 (China Academy of Information and Communication Technology, 2015b). The market for big data was approximately CNY 8.4 billion (USD 1.3 billion) in 2014. China's big-data market is expected to grow by around 40% a year over 2016-18 (China Academy of

Information and Communication Technology, 2015a). Meanwhile, sales from China's electronic information industry exceeded CNY 14 trillion (USD 2.2 trillion) in 2014 (Ministry of Industry and Information Technology, 2015b).[2] The R&D capabilities in China are also catching up with global leaders (Figure 12.4).

Figure 12.4. **Leading countries in Internet of Things (IoT) and big-data technologies (2005-07 and 2010-12)**

Economies' share of IP5 patent families filed at US Patent Office and the European Patent Office selected ICT



Notes: Data refer to IP5 patent families filed at the European Patent Office (EPO) or the US Patent Office (USPTO), by first filing date and according to the applicant's residence using fractional counts. The United Kingdom's Intellectual Property Office (IPO) has allocated patent documents to technology fields. BRIICS = Brazil, the Russian Federation, India, Indonesia, China and South Africa.
Source: OECD calculations based on IPO (2014), "Eight Great Technologies: the Patent Landscapes", *www.gov.uk/government/uploads/system/uploads/attachment_data/file/360986/Eight_Great_Technologies.pdf* and OECD (2015c), *STI Micro-data Lab: Intellectual Property* database, *http://oe.cd/ipstats* (accessed June 2015).

StatLink http://dx.doi.org/10.1787/888933473916

The Internet of Things (IoT)

It has been estimated that applying the IoT in Chinese manufacturing could add USD 196 billion to GDP over the next 15 years (Accenture, 2015). The industrial IoT in China has seen most success in machinery equipment manufacturing, the automotive sector, iron and steel (CCID Consulting, 2015a). The IoT has mostly been applied to supply chain management, processes optimisation, and equipment and energy consumption monitoring (China Academy of Telecommunication Research, 2014b). Machine-to-machine (M2M) services have flowered in China. By the end of 2014, there were 74 million domestic connections between machines, making China the largest M2M market globally (GSMA, 2015).

Wuxi City, a municipality in Jiangsu Province, has been a part of the Institute of Electrical and Electronics Engineers' (IEEE) Smart Cities Initiative. And Wuxi No. 1 Cotton Mill, one of the city's largest textile manufacturers (dating back to 1919), is considered an example of success in upgrading through the IoT. The company updated its production line with over 90 000 sensors and 28 systems to monitor production, quality control and energy consumption. The number of workers per 10 000 spindles was reduced from more than 100 to 25, and the energy saved per year amounts to over CNY 8 million (USD 1.6 million) (Su, 2014).

Besides optimising manufacturing processes, the IoT can also enable the creation of new services and businesses for manufacturers. For example, since 2007, Sany Heavy Industry, a heavy machinery manufacturer, has developed an enterprise control system which retrieves

data and monitors operations through sensors and controllers pre-installed in products. Based on these data, feedback and recommendations are provided to customers using real-time monitoring, corrective maintenance and debugging support. The data also facilitate in-house R&D. Over 200 000 machines now run on this platform according to the company.

Cloud computing

Chinese manufacturers principally use cloud computing to improve the utilisation of information technology (IT) infrastructures and reduce the costs of enterprise resource planning (ERP). In 2014, the major industrial cloud computing services offered in China were infrastructure-as-a-service (IaaS), such as cloud hosting, cloud storage and cloud network services, and software-as-a-service (SaaS) (CCID Consulting, 2015b) (Box 12.1).

Enabled by cloud computing, the idea of intelligent cloud manufacturing has also been proposed in China, in which manufacturing resources and capabilities are provided as cloud services, available to end users through the Internet or cloud manufacturing platforms. Shenyang Machine Tool Group (SMTCL), the world's second largest machine tool manufacturer in 2014 (Statista, 2014), introduced its i5 intelligent machine tool based on this idea. Each machine is connected to a cloud platform. A dedicated application is provided to end users, allowing them to create designs and models to be uploaded to the platform and manufactured by available machines. To further facilitate its vision of "idea to shape", the company established another platform that analyses data from customers, designers and the company's machines, and promotes collaborations in areas ranging from demand identification to design and production. In this way, SMTCL aims to shift from being a pure manufacturer to being an industrial productivity service provider, and to profit by charging for machine running hours, instead of simply selling machines (OFweek, 2015).

Big data

Growing use of digital technologies creates expanding volumes of data. Indeed, in the platform-as-a-service sector, big-data analysis is the most popular service among industrial users in China (China Academy of Information and Communication Technology, 2015b). The year 2014 is considered the beginning of the industrial big-data market in China (China Academy of Information and Communication Technology, 2015a).

In manufacturing, more than 75% of big-data applications are intended to establish closer connections with customers, mainly by attracting customers and improving the customer experience. Only 10% of applications aim to track products or analyse the operation of equipment (Minglamp Consulting, 2015). This corresponds with the general pattern of big-data use in China, in which big data, generated mainly from within companies and analysed using traditional procedures, is then used for Internet-based marketing or for improving existing products and services (China Academy of Telecommunication Research, 2014a).

Empowered by big data, Motorola Mobility can predict customer preferences regarding the colour and materials of mobile telephones and prepare production accordingly. The company introduced Moto Maker, offering over 2 000 combinations for customers to choose from for their telephones. Haier Group, China's leading manufacturer of home appliances and consumer electronics, is also working with the Alibaba Group, owner of the largest online sales platform in China, to use consumer preferences data from Alibaba and provide more customised end products.

Domestic manufacturers also play an important role in supplying infrastructure for digital technologies. Most of China's server market is supplied by domestic manufacturers, and the top four companies (Inspur Eletronics, Lenovo, Huawei and Sugon) have grown their combined revenues by 19.5% a year due to a robust home market in 2015 (IDC, 2016).

Digital technologies have opened manufacturing to Chinese Internet companies

Chinese Internet companies not only lead the domestic market in cloud computing (Box 12.1), the IoT and big data, they are also extending their influence over traditional industries, including manufacturing. For example, at the beginning of 2015, Baidu Inc., China's largest Internet search company, introduced its cross platform system, CarLife, which will connect its online map service with car manufacturers and customers. The company also finished testing a driverless vehicle system in December 2016, claiming a top speed of 100 kilometres per hour during the test (Baidu, 2015). Alibaba, after investing CNY 6 billion (USD 944 million) in its AliCloud business, is ambitiously promoting a shift from IT to data technology (DT) (AliResearch, 2015). With its huge data resources, the company aims to implement cross-industry applications in sectors ranging from robotics, the IoT and biotech, to financing and infrastructure. For this purpose, the company now hosts an annual computing conference in Hangzhou City. In April 2016, the core development team of BMW's i3 and i8 electric vehicle line joined the Future Mobility Corp, a Chinese start-up backed by Tencent Holdings, another major Chinese Internet company (Boston, 2016).

Box 12.1. **Cloud computing and the Chinese New Year**

In recent years, as the Chinese new year approaches, many Chinese go through three major events linked to cloud computing: shopping online in the Double 11 Festival, buying Spring Festival train tickets on 12306.cn and offering *hongbao* (gift money) on social applications on the eve of the lunar new year. As described below, these three instances show how the size of China's market demand has stimulated and shaped the application of cloud computing, and how, in turn, cloud computing has created market demand.

For China's youth, 11 November is known as Single's Day, a day on which young singles celebrate their singleness. On this day in 2009 Alibaba initiated an online promotional event, yielding CNY 52 million sales. By 2013, Alibaba's sales on 11 November were twice those of online sales in the United States on Black Friday and Cyber Monday combined (Yan, 2014). A hybrid cloud computing structure has been used since 2015, in which the trade and payment systems are hosted by the public cloud, while the other businesses are hosted by the private cloud. This has helped the site to handle surging visits over a short period without having to buy extra servers. In 2016, Alibaba alone registered sales worth CNY 120.7 billion. The company's website handled 120 000 transactions per second at the peak of demand and over 1 billion transactions in a single day (Xinhua, 2016).

If there is anything harder to obtain than half-price limited version items for the Double 11 Festival, it is a train ticket to go home at the Spring Festival holiday. 12306.cn, China's official online train ticket sales portal, fared badly when it premiered in 2012 and crashed under an unexpected peak of 1.4 billion hits in a single day (Caijing, 2012). Managing the sale of Spring Festival train tickets is difficult not only because the site is subject to surging concurrent visits, but also because such ticket sales are complicated. Where the available number of certain online goods can be calculated by using stock numbers minus numbers sold, this is not the case with the number of available train tickets. For a route with stops from A to E, when one buys a ticket from B to D, this changes the availability of tickets for all the

Box 12.1. **Cloud computing and the Chinese New Year** *(cont.)*

overlapping journeys (such as A to C), while also taking account of different types of seats and co-ordination with sales from offline channels. 12306.cn started using cloud computing in 2014 and has collaborated with Alibaba since 2015. The cloud handles over 75% of inquiries for available tickets and has helped 12306.cn avoid major site crashes (Li X., 2016). The site handled a peak of 29.7 billion page visits a day for the 2015 Spring Festival, and boasted a 30% efficiency increase, and a mere 1.8 seconds of online queueing, in 2016 (Nandu Daily, 2015).

When Chinese return home for the Spring Festival – with tickets from 12306.cn and gifts from Double 11 – they will probably also prepare hongbao for the family. Traditionally these are gifts of money packed in red envelopes given and received with ceremonial reverence. But now hongbao are available in the form of social applications. In 2015, WeChat, China's most popular messaging application, developed by Tencent, collaborated with China Central TV (CCTV) in the most watched lunar new year's gala ever, in which at certain times the hosts asked the audience to shake their mobile telephones to receive hongbao. Over 1 billion hongbao were sent and received. An application of such scale would not be possible without cloud computing, to address surging use and financial security (Teng, 2016). Such developments have also brought the technologies much closer to the ordinary citizen. A recent survey found that 75% of mobile payment users in China use mobile payments in physical stores daily (Alvin Wu, 2016).

Policy settings in China on digital technologies

To support the development and industrial use of digital technologies, Chapter 2, on digital technologies and production, suggests that governments need to develop coherent data governance frameworks, promote open standards and responsible use of personal data. Governments are also advised to develop an innovation policy mix that encourages investments in data (its collection, curation, and reuse) and R&D in fields including big-data analytics, cloud and high-performance computing, IoT, and security- and privacy-enhancing technologies. Barriers for data reuse and sharing, market competition, and the adoption of ICT need to be examined and addressed if necessary. Demand-side policies can be considered to encourage the adoption of key enabling ICTs, especially by small and medium-sized enterprises (SMEs). It is also advised to support a culture of digital risk management, and develop ICT-related skills, especially in collaboration with the business.

Data policies recently discussed in China largely concern big data

The Action Plan to Promote the Development of Big Data, released by the Chinese State Council in August 2015, identified three major tasks for developing big data in China: open access and better governance of public data, innovative business models within and across industries, and data security. China has begun ten key projects, ranging from data sharing among government departments to cross-industry data use (in manufacturing, services and agriculture).

China's 13th Five-Year Plan, released in March 2016, considers big data to be a strategic resource and formulated a National Big Data Strategy, focusing on open access to government data, R&D and application of big data technologies. An inter-ministerial mechanism will co-ordinate different government bodies, led by Ministry of Industry and Information Technology, National Development and Reform Commission and Cyberspace

Administration of China, with emphases on cross-government data sharing, industrial innovation and data formats and standards.

A standardisation system for data is being developed, covering data collection, categorisation, exchange, formatting, trade and security. Demonstration projects will be implemented for data trading and standards evaluation (the approach is one of top-down opening up of government data, instead of bottom-up non-discriminatory data access.)

The Made in China 2025 and Internet Plus initiatives discussed later in this chapter aim to build an Industrial Internet system and create more open and synchronised data flows across stages of manufacturing.

Many regions, such as Beijing, Shanghai, Zhejiang, Guangdong and Guizhou, have released plans to support big data. Among them, Guizhou released China's first regional regulation on big data, which outlined key measures for the application, sharing and security of big data. In an effort to promote data flow and exchange, the Global Big Data Exchange was set up in 2015 in Guiyang City, the capital of Guizhou. This exchange includes data from sectors such as finance, education, energy and logistics. Such exchanges are also being set up in Beijing, Shanghai and other cities across China.

Key national research projects have been set up on ICTs and technology adoption is being encouraged

The central government allocated around USD 58 million for cloud computing and big data in the 2016 National Key Technology R&D Program, and USD 46 million was earmarked for high-performance computing. An IoT development fund was set up by the Ministry of Finance and Ministry of Industry and Information Technology in 2011, with an initial annual budget of up to USD 75 million. Following the 2013 State Council's Opinions concerning Promoting the Co-ordinated Development of the Internet of Things, an action plan was initiated across various ministries to cover national strategy, standards, applications, business models, security, law and regulations, and the required human resources.

The Integration of Industrialisation and Informatisation is a key initiative begun in 2007. Government funds have promoted the application of numerical control and digital design in traditional sectors such as steel, ship building, textiles and mining. A national management system standard (GB/T23000-23999) is being developed. This will help guide companies seeking to further adopt ICTs.

By opening selected markets to the private sector, the government has sought to address barriers to ICT adoption, such as high prices and lack of competition. Since 2013, mobile network operators have been able to enter markets previously dominated by SOEs. Since 2015, providing broadband services is also open to the private sector. Regulations on setting up a business have been streamlined, e.g. by reducing the number of required licences, and policies have been implemented to facilitate Internet-based financing and new services, such as Internet ride-hailing services.

Policies in China focus on providing wider Internet access, improving Internet speed, building the Industrial Internet, and encouraging Internet related start-ups

The State Information Strategy (2006-20), aims to build a national information infrastructure covering most of the population by 2020. The 2013 Broadband China initiative aims to provide broadband coverage for 70% of families and mobile broadband service for 85% of households by 2020. The speed and pricing of Internet access were also addressed in

State Council guiding opinions in 2015. These recommended free upgrading of threshold broadband speed (up to 4 megabytes per second), as well as lower mobile data pricing.

The July 2016 State Information Technology Strategic Outline sets targets to 2025 for fibre broadband access in rural areas, national 4G network coverage, and an international Internet bandwidth of 48 Tbps. By June 2016, 710 million people had Internet access, 92.5% of which have access to mobile Internet. However, a large gap remains between urban and rural areas (67.3% coverage compared to 31.7% respectively).

The government is also examining how to ensure cybersecurity

In November 2016 China's first law on national cybersecurity was approved by the Standing Committee of the National People's Congress. The law sets out regulations on cyber sovereignty, the responsibilities of cyber service providers and network operators, protection of personal information and infrastructures, and cross-border data transmission. There is as yet no dedicated national law on personal privacy protection in China.

In June 2016, the second US-China High-Level Joint Dialogue on Cybercrime was held in Beijing, with outcomes on information sharing, case co-operation and network protection. Around USD 31 million is allocated for cyberspace security in the 2016 National Key Technology R&D Programme.

Measures to develop digital skill are also being taken

In 2000, the Chinese Ministry of Education released guidelines for ICT education in primary and middle schools. ICT courses became mandatory in 2005 in all middle schools, as well as in primary schools in more developed regions. In 2013 the Ministry of Education initiated a national training project to develop ICT skills among teachers in middle and primary schools (including kindergartens). The aim is to cover 10 million schools by the end of 2017. This is a part of China's ten-year plan for IT in education (2011-20). The Ministry of Education is now developing teaching guidelines for robotics in primary and middle schools.

In higher education and career education, courses are to be created on ICT application. The Action Plan to Promote the Development of Big Data encourages colleges to set up programmes in data science and data engineering.

Industrial robotics

The application of robotics, especially industrial robots (IRs), is a direct response to labour shortages and the demand for higher quality output in China. Over 2008-13, the supply of IRs increased by about 36% per year on average in China. China was the world's largest market for IRs in 2013 and 2014, and by 2017 is expected to have up to 428 000 units, the largest number of industrial robots in use in any country (International Federation of Robotics, 2015). Among the 56 000 IRs sold in China in 2014, domestic robot manufacturers supplied 16 000 units, with the rest coming from foreign firms such as ABB, Kuka, Yaskawa and FANUC (Reuters, 2015). In R&D, China was among the top five countries in robotics first patent filings during the period 2005-11 (World Intellectual Property Organization, 2015). Meanwhile, other related technologies, such as artificial intelligence (AI), are developing fast (Box 12.2).

In spite of rapid growth in the use of IRs, robot density in China in 2014 was 36 units per 100 000 employees, below the global average of 66. In the automotive industry, robot density was 305, while density in key automotive manufacturing countries (such as Japan, Germany, the United States and Korea) is above 1 000 (International Federation of Robotics, 2016).

Box 12.2. **Creating new hardware for artificial intelligence (AI)**

In the field of artificial intelligence, machine learning has created huge and specific demands for computing power and efficiency. The DianNao (the Chinese word for computer) hardware family and Cambricon-1A chip are among the latest to seize this unique and potentially high-value opportunity.

Machine learning is already widely used, in applications ranging from speech recognition in Google assistant and Siri, to face identification in image applications, to autonomous driving. Presently convolutional and deep neural networks (CNNs and DNNs) are among the state-of-the-art and most extensively used deep learning algorithms, but both are computationally and memory intensive. Conventionally, these algorithms are run on general-purpose processors (such as CPU and GPU), which are often not the most efficient options, as these processors are not tailored for such tasks (Keutzer, 2016). For example, to train a DNN to identify a cat's face, it took the Google research team 1 000 machines, 16 000 cores and 3 days (Le et al., 2012). Consequently, machine-learning applications are becoming major drivers of high-performance computing (Chen et al., 2014).

The DianNao project was born in this context. The project started as an international collaboration between the State Key Laboratory of Computer Architecture and the French Institute for Research in Computer Science and Automation, and developed the DianNao family, a series of hardware accelerators specially designed for machine learning. On a DaDianNao system (the term means a big computer with a DianNao family multi-chip architecture), it is possible to operate 450.6 times faster than a GPU, and reduce energy by 150.3 times on average (Chen et al., 2016). This research has received two best paper awards in the field of computer hardware (ASPLOS 2014 and MICRO 2014).

Based on the initial research, the Chinese team further developed Cambricon, a more versatile instruction set architecture for neural networks, started as a spin-off under the same name. Cambricon has released the Cambricon-1A, which is claimed by the company to be the first chip dedicated for high-performance neural networks applications (Gu, 2016). The Cambricon-1A was also selected as one of the 15 Leading Internet Scientific & Technological Achievements at the third World Internet Conference (CCTV, 2016).

While industrial robots have become a key feature of the automotive sector, the application of IRs in the electronics sector is also advancing. Since 2010, Hon Hai Precision Industry, a leading Chinese manufacturer best known for making iPhones for Apple, has used IRs developed in-house in its Kunshan City factory in the Yangzi River Delta. The company reduced employees in the factory from 110 000 to 50 000, while revenue reportedly increased (Zhu, 2015). The company aims to achieve 30% automation in its factories in China by 2020. Together with Alibaba, Hon Hai holds a 20% share of Japan's SoftBank Robotics Corp. Since June 2015, the latter makes and sells Pepper, a robot able to understand some human emotions (Inagaki, 2015).

While most of the IR market is supplied by foreign suppliers, rapid development and application of IRs in China has led domestic companies to manufacture their own IRs. Sales of domestic IRs increased 77% in 2014, relative to 2013 (Shen, 2015).

SIASUN Robot & Automation, affiliated to the Chinese Academy of Sciences, is a leading domestic robotics company. Three-quarters of the company's 1 600 workers are reportedly employed in R&D, with only around 200 working on the assembly line (Liu, 2015). The company introduced a digital smart factory in 2014. This factory uses robots to

produce robots, integrating SIASUN's in-house robotic capabilities in logistics, assembly and quality inspection, and is able to produce 5 000 IRs annually (He, 2015).

Chinese manufacturers which intend to enter the IR market without previous experience are also using acquisitions. For example, in May 2016, the Chinese consumer appliance company Midea made a EUR 4.5 billion offer for Kuka, a leading German robotics company. It was announced in August 2016 that 81% of Kuka's shares had been tendered for an offer made by Midea (Thompson, 2016). The deal is now in a process of regulatory approval.

Policy settings in China on robotics

In the National Development Plan for Robotics (2016-20), the government focuses on developing a robotics industry system capable of producing IRs with technical specifications and qualities on a par with international competitors, and aims to achieve a 45% market share for domestic companies in high-end robotics by 2020 (Ministry of Industry and Information Technology, 2015d). Besides IRs, the government also aims to facilitate mass production and application of service robots for seniors, health and medical care.

A technology roadmap for robotics was issued as a follow-up to Made in China 2025. The roadmap identifies the key technologies and components for developing IRs and service robots, and suggests strengthening co-ordination between research and application, standardisation, and quality assessment and certification at national level. In November 2016, China announced a robot certification mark and issued the first certificates to around 20 manufacturers.

Regions in China with traditional strengths in manufacturing mechanical and electrical products, including the Yangzi River Delta and the Pearl River Delta, have initiated large-scale "robot replaces humans" programmes. For example, from 2015-17, Guangdong province aims to promote the programmes in over 1 950 enterprises with annual revenues of CNY 20 million (USD 3.1 million) or more (Government of Guangdong, 2015).

3D printing

3D printing, more commonly referred to in China as additive manufacturing, is another technology which China's State Council considers key to advanced manufacturing.

3D printing is developing rapidly in China. From 1988-2014, 79 602 industrial 3D printers were installed worldwide. During this period, in the world market for 3D printers costing USD 5 000 or more, China ranked 3rd, accounting for 9.2% of the total units in use, behind the United States (38.1%) and Japan (9.3%) (Parker, 2015). From 2013-14 the market for 3D printers in China increased from CNY 2 billion (USD 315 million) to CNY 3.7 billion (USD 582 million) (Huang, 2015), and is expected to reach CNY 10 billion (USD 1.6 billion) by 2016, according to the China 3D Printing Technology Industry Alliance. By April 2015, China ranked third in the global number of 3D printing patents, behind the United States and Japan (Feng F., 2015). Industrial 3D printing in China is under way in such sectors as space and aviation, biomedicine and the automotive industry.

The Commercial Aircraft Corporation of China (COMAC) has used 3D printing in making the ARJ 21 regional jet, and 3D printing will be used in manufacturing the C919, China's first domestically designed commercial aircraft. With 3D printing, making the hyperboloid cockpit window frames of the C919 will take around 55 days and cost less than USD 200 000 a unit, compared to two years and USD 2 million if done traditionally (Ren, 2014).

Announced in September 2015, and approved by the Chinese Food and Drug Administration, China's first 3D printed hip replacement has been made available to the public. This hip replacement offers high customisation, but is only half to one-third the cost of the previously imported replacements (Xinhua, 2015).

In consumer manufacturing, 3D printing has seen growing use in jewellery design and personalised applications, such as 3D printing for personal portraits and toys. Around 50% of jewellery makers in Guangzhou City use 3D printing in jewellery design (Cui and Liu, 2015). Claiming the highest standard of precision globally, a 3D printing service centre began operating in July 2015 in Foshan City, Guangdong Province. The largest of its kind in China, and using up to 1 000 Stratasys Solidscape printers, this centre aims to serve China's domestic jewellery industry, among other customers (China South Daily, 2015).

However, at present, most industrial 3D printers in China are used in sectors such as research, education, aviation and design, which focus on R&D applications, especially the manufacturing of prototypes (Min, 2015). Restricted by the lack of standardisation with respect to the quality of 3D printed objects, the higher price of key 3D printing materials, and limited market demand for flexible and customised production, 3D printing is taking time to shift from small-scale, high-precision technology and design-centred production to industrial scale production.

Domestic manufacturers using 3D printing in China are usually supported by, or initially spin off from, major national universities and research institutes. For example, in industrial 3D printing, Shaanxi Hengtong Intelligent Machines, which is also hosting the first National Engineering Research Centre for Rapid Manufacturing, originated from Xi'an Jiaotong University. And Wuhan Binhu Mechanical & Electrical, the manufacturer of China's first 3D printer with independent intellectual property, came out of Huazhong University of Science and Technology.

Desktop 3D printing is also booming in China. Tiertime, which began as a start-up out of Tsinghua University, is now the largest manufacturer of 3D printers in Asia, and 70% of its sales are to overseas markets (Li H., 2015). Also from Tsinghua University, AOD 3D Printing was created by a PhD graduate and was supported by the Tsinghua X-lab incubator. The company raised nearly CNY 5 million (USD 787 000) in 24 hours through WeChat-based crowd funding (WeChat is the most popular instant messaging application in China) (X-lab, 2014). The company's main product, the AOD Artist 3D printer, which is tailored for artists and designers, is sold online at JD.com, one of China's largest online direct sales platforms.

Policy settings in China on 3D printing

Chapter 5, on 3D printing and its environmental impacts, suggests that to encourage sustainability in 3D printing, policy should primarily encourage low-energy printing processes and low-impact materials (such as compostable biomaterials) that have useful end-of-life characteristics. Intellectual property barriers may need to be removed for potential applications of 3D printing, such as the making of repair parts for legacy products that lack existing supply chains.

In China, a national plan for promoting additive manufacturing (2015-16) was released in 2015, focusing on research directions including feedstock (metal, non-metal and specific materials for medical purposes), process technologies (both melting and chemical processes), and key devices (such as melting and feeding devices and high-precision sprinklers). The plan also aims to develop an industrial standard system and to initiate

demonstration projects. Aerospace and aviation, automobile engine, industrial prototyping and high-precision medical devices are among the industrials targeted for application and commercialisation.

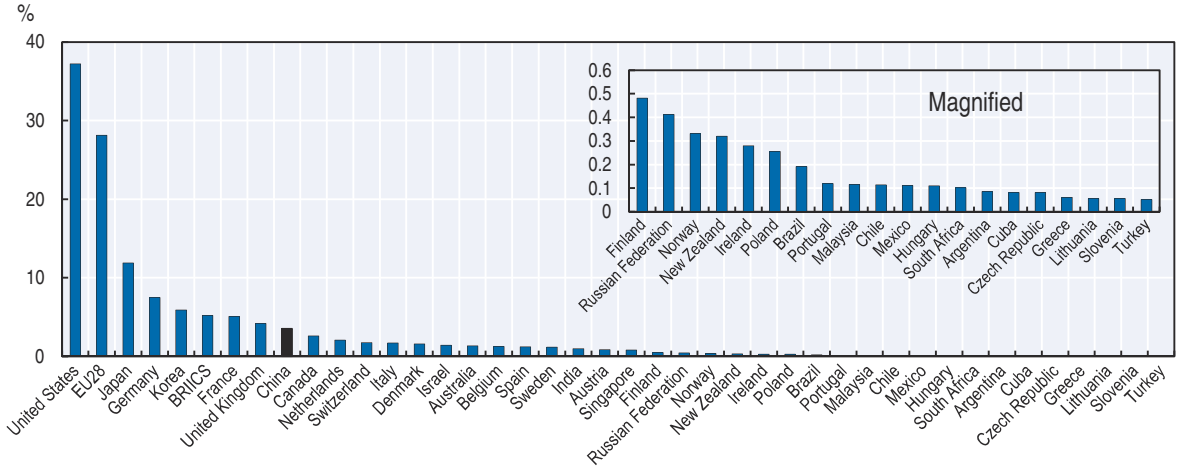
In 2016, a national research project, with a budget of CNY 400 million, was started for additive manufacturing and laser manufacturing. Among the seven priorities of the former, five aim at commercialisation and must be led by enterprises. A standards technology committee and an industrial alliance for additive manufacturing were also established in 2016. A project supported by the Chinese Academy of Social Sciences was initiated in 2014 to study the development of 3D printing and the changes it could require in the intellectual property system.

At regional level, voluntary certifications exist for additive manufacturing (e.g. from the Additive Manufacturing Products Supervision and Inspection Center of Jiangsu Province). These mostly focus on quality, rather than sustainability.

Biotechnology

Biotechnology is listed as one of eight "frontier" technologies in the Guidelines on National Medium- and Long-term Program for Science and Technology Development (2006-20). From 2010-13, China ranked seventh in the global share of biotechnology patents (Figure 12.5) (OECD, 2015b). Bioindustry output in China reached CNY 3.16 trillion (USD 497 billion) in 2014, equivalent to 4.6% of GDP (Fu and Feng, 2015). In Made in China 2025, biomedicine and bio-based materials are specifically considered parts of advanced manufacturing.

Figure 12.5. **Country shares in biotechnology patents, 2010-13**



Notes: Data refer to patent families filed within the Five Intellectual Property Offices (IP5), with members filed at the EPO or at the USPTO, by the first filing date, the inventor's residence using fractional counts. BRIICS = Brazil, the Russian Federation, India, Indonesia, China and South Africa. Data from 2013 are estimates.

Source: OECD (2016b), *STI Micro-data Lab: Intellectual Property* database, *http://oe.cd/ipstats* (accessed October 2016).

StatLink *http://dx.doi.org/10.1787/888933473920*

Production of biomedicines is the leading sector in China's bioindustry

In 2009, production of biomedicines reached CNY 1.04 trillion (some USD 164 billion) (overall bioindustry output in the same year was CNY 1.4 trillion) (Ministry of Science and Technology, 2011). For the period 2013-15 the government established three major policy aims:

development and industrialisation of biologic medicine; quality improvement in chemical medicine; and, standardisation of traditional Chinese medicine (State Council, 2013).

The government is implementing stricter standards for drug production, while implementing policies to attract talent and encourage drug development. Chinese companies are trying to catch up in biomedicine, both in manufacturing and in drug development. Entrepreneurs with an overseas education and business background are playing a major role. For example, WuXi AppTec, founded by a Chinese returnee, is a leading pharmaceutical contract research company and manufacturer. The company produces the compound IMP321 (for the French drugmaker Immutep), a biologic cancer treatment in late-stage development. Frederic Triebel, Immutep's scientific and medical director, noted that "Five years ago, no one would have been talking about manufacturing in China. But now, it's accepted that it's the place to go." (Deng, 2014). AppTec also produces Ibalizumab, a biologic to treat HIV, for Chinese Taipei's TaiMed Biologics. Ibalizumab received "breakthrough therapy" designation from the US Food and Drug Administration (FDA) in 2015 (Chizkov and Million, 2015). AppTec claims that if the FDA approves Ibalizumab, it would be the first biologic medicine manufactured in China to be launched in the United States.

In December 2014, Chidamide, a chemical medicine developed by Chipscreen Ltd., was approved by China's FDA for the treatment of peripheral T-cell lymphoma. Chidamide is considered the first medicine entirely developed in China, and has been cited as an example of China's pharmaceuticals industry shifting from copying to innovation (Peng, Feng and Bai, 2015). Lu Xianping, co-founder of the company, and another returned entrepreneur, estimates the cost of research to develop chidamide at about USD 70 million, around one-tenth what it would have cost to develop in the United States (Wang, S., 2015).

Biomedical engineering in China

Acornea, jointly developed by China Regenerative Medicine International (CRMI) and the Tissue Engineering R&D Centre of the Fourth Military Medical University, is a bioengineered cornea, the research for which has been supported by the government (the cornea received approval from China's FDA in April 2015). Now in wide production, this product is expected to relieve the acute shortage of corneas in China (Chen, 2015). "It is the world's first bioengineered artificial cornea that completed clinical trials and obtained a medical certificate," reported the chief executive of CRMI (Yang Jing, 2015).

BGI, one of China's leading companies in gene sequencing and genetic tests, aims to provide precision medical services by combining its strengths in genomics, big data and AI. BGI works with local partners, including Huawei and the National Super Computer Centre, on big-data storage and processing. BGI has established an online gene test platform, GeneBook, which provides prenatal gene diagnosis, gene diagnoses for breast cancer and dementia, and genetic assessment of tolerance to alcohol.

Sales of bio-based materials were projected in 2012 to reach CNY 750 billion in 2015 (USD 118 billion), and to play an increasingly important role in replacing petrochemical materials and chemical processing technologies (State Council, 2013). China is active in industrial production of and research on polyhydroxyalkanoates (PHAs) (an eco-friendly bio-based material used for producing bioplastics) and increasingly active in the area of industrial fermentation, biofuels and bioimplants (Chen and Wang, 2015).

Around 700 million tonnes of straw biomass is generated annually in China (Ministry of Science and Technology, 2015a). Pilot projects have been implemented to produce

industrial sugar and biofuel, and biorefineries are expected to make further use of the straw biomass. A second-generation biorefinery, with an estimated capacity to take 970 000 to 1.3 million tonnes of straw biomass feedstock a year, is being built in Anhui Province in eastern China, through a joint venture between China's Anhui Guozhen Group and Italy's M&G Chemicals (Voegele, 2014).

Synthetic biology – including bio-based material manufacturing using synthetic biology – has been supported since 2011 by China's National Basic Research Programme. BluePHA, a start-up from Tsinghua University, is developing a seawater-based fermentation process that produces PHA at low cost (Yue, Ling and Yang, 2014). One of the targeted applications for the PHA will be as a material to be used in 3D printing.

Policy settings in China on biotechnology

Chapter 3, on biotechnology and future production, suggests that policy to support innovation in bio-based chemicals should help to create sustainable supply chains for bio-based production and recognise the need for demonstrator- and commercial-scale biorefineries. Governments often also need to fill gaps in research and training, improve the regulatory environment, and lead in market-making through public procurement policies.

Starting from the 11th Five-Year Plan (FYP), China has issued policies and plans for developing its bioindustry. National projects were dedicated to the bio-based material industry in the 12th Five-Year period (2011-15), with support for basic research and key bio-based materials and chemicals. By the end of 2012, the State Council released a National Strategy for the Bioindustry, which among other things initiated demonstration projects for bio-based materials and chemicals. By 2015, bio-based chemicals ranked third in patent applications in China's bioindustry, following biomedicine and biomedical devices.

By regulation, bio-based production in China must be based on non-grain crops. An action plan was initiated under the 2012 National Strategy for the Bioindustry to build a supply system for non-grain crops that included five to ten production areas of non-cropland and multiple biosources, such as sweet sorghum and cassava. However, stable and sustainable feedstock supply for bio-based production remains a key challenge.

While demonstration projects are under construction, there are as yet no policies in China concerning biorefineries.

In terms of human resources, a mid- and long-term national talent development plan for biotechnology (2010-20) was published in 2011. This aims to develop researchers and research teams through national projects, and through research institutions such as national labs and engineering centres. The plan also focused on industry by utilising national high-tech parks to start demonstration projects and to increase the number of experienced industrial workers. Managers will also be trained through national training programmes.

A technology committee for the standardisation of bio-based material and biodegradable products was established in 2008, and was included in the Guidelines for the Standard System of Green Manufacturing. However, further national standards on bio-based materials are needed. At regional level, many provinces (e.g. Jiangsu, Shangdong) have issued regulations on the circular economy (for example, promoting bio-based and biodegradable products, e.g. by banning non-degradable plastic bags).

Biomass waste constitutes 11% of China's industrial solid wastes and less than 10% of those were recycled in 2010 (Ministry of Environment Protection, 2012). A national project for utilising such waste was initiated in the 12th FYP. Among its technology goals was a 90%

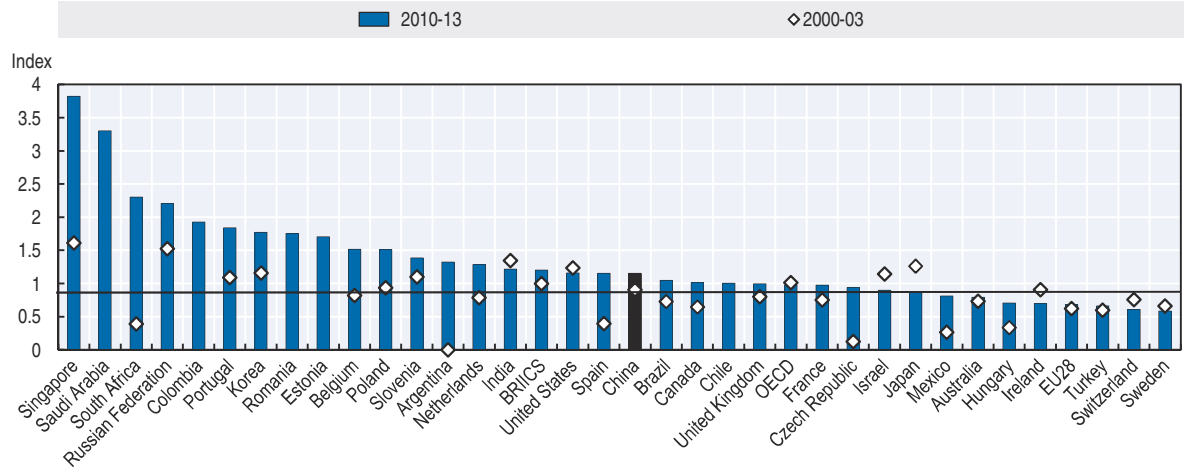
utilisation rate of industrial biomass waste in fuel gas generation. Similar approaches were also taken to domestic waste.

A 2009 State Council document considered promoting the bioindustry through public procurement. Implementation occurred at regional levels. For example, Shenzhen City issued a green procurement list and included the use of bio-based and degradable materials in the system for assessing the quality of hotels and restaurants.

Nanotechnology

China began research in nanotechnology in the middle of the 1980s. By the end of the 11th FYP (2006-10), China ranked first in Science Citation Index publications in nanotechnology and second in total citations (Ministry of Science and Technology, 2012a). During 2010-13 China ranked fourth in the global share of nanotechnology patents and increased its revealed technological advantage in nanotechnologies (Figure 12.6) (OECD, 2015b). With its achievements in research, China now aims to translate research to commercial use. Successful industrial applications of nanotechnology in China have seen frequent collaborations among research institutes, universities and industry.

Figure 12.6. **Revealed technological advantage in nanotechnologies, 2000-03 and 2010-13**



Notes: Data refer to patent families filed within the Five Intellectual Property (IP) Offices (IP5), with members filed at the EPO or at the USPTO, by the first filing date, the inventor's residence using fractional counts. The revealed technological advantage index is calculated as the share of the country (or economy) in nanotechnology patents relative to the share of the country (or economy) in total patents. Only countries and economies with more than 100 patents in the two periods are included in the figure.
Source: OECD (2016b), *STI Micro-data Lab: Intellectual Property* database, *http://oe.cd/ipstats* (accessed October 2016).
StatLink http://dx.doi.org/10.1787/888933473936

Nanomaterial accounts for the largest share of China's patents in nanotechnology. The concept of new materials covers a very wide spectrum of materials. The 12th FYP listed over 400 key materials (across metallic, semi-conducting, composite, polymer, inorganic and "frontier" materials). According to the latest data, production in the new material industry increased from CNY 600 billion in 2010 to CNY 2 trillion in 2015.

Among nanomaterials in China, research on, and application of, carbon nanotubes (CNT) have grown particularly fast. Currently, the touch screen market is dominated by indium tin oxide (ITO) film and glass technology. However, constrained by limited screen size and the high price of indium, ITO is being challenged by other technologies, including CNTs (Heo, 2013). CNTouch, jointly established by Tsinghua University and the Foxconn Group, can replace ITO

with CNT in touch screens, which in turn reduces production costs and the thickness of the panels. CNTouch collaborates with major Chinese mobile telephone manufacturers including Huawei, ZTE and Lenovo, and had revenues of around CNY 400 million (USD 63 million) in 2013 (Tianjin Municipal Science and Technology Commission, 2014).

Chinese manufacturers are also key players in the global market for CNTs. Cnano Technology Limited, with a CNT production capacity of 500 tonnes per year, and TimesNano, which is affiliated with the Chinese Academy of Sciences and has a capacity of 200 tonnes per year, are expected to lead the global CNT market as their output increases (Johnson, 2014). The two companies are also major manufacturers of CNT conductive pastes, which are used to increase performance in lithium-ion batteries.

Besides CNT, nanocomposites are increasingly used as a coating material, and industrial application has occurred in electrical engineering. China is building a national ultra-high-voltage electricity transmission system. Climate conditions and air pollution pose challenges for this system, which requires high-performance coatings in electrical insulation to prevent pollution-related flashovers (Zhang et al., 2013). To respond to this need, a nanocomposite coating is being developed jointly by State Grid and the Chinese Academy of Sciences, and has been applied in anti-pollution coating projects in a number of 500 kilovolt (kV) and 220 kV booster substations.

Nanoscale catalysts have been applied in China in coal-based ethylene glycol production. Nanocatalysts developed by the Fujian Institute of Research on the Structure of Matter (a part of the Chinese Academy of Sciences) are considered essential for such glycol production. The Fujian Institute of Research now works with Danhua Chemical Technology and Shanghai Gem Chemicals Hi-tech in industrialised production, and aims to reach a capacity of 3 million tonnes per year (Hanhua Technology, 2013). The institute is also co-operating with Guizhou Province to implement its second generation of coal-based ethylene glycol production. Due to ethylene glycol's wide application in the chemical industry, and China's rich coal resources, industrialised coal-based ethylene glycol production is considered an important breakthrough in China (Ministry of Science and Technology, 2012b).

A research team at the Dalian Institute of Chemical Physics has achieved direct and non-oxidative conversion of methane to ethylene, aromatics and hydrogen (Guo, 2014). This development was listed as one of the top ten scientific achievements in China in 2014 (Sciencenet, 2015). Industrialisation of such technology, if successful, has great potential to more effectively utilise natural gas and shale gas.

Nano-printing technology, combined with metal nanomaterials, promises industrial applications in the production of printed electronics, such as radio-frequency identification (RFID) circuits, electronic tickets, antennae, flexible displays and lighting. NanoTop Electronic Technology, a company jointly supported by the Beijing municipal government, Lenovo Group and the Chinese Academy of Sciences, produces electronic tickets using nano-printing and nano silver composite paste. A pilot project of 200 000 RFID tickets has been implemented in the Beijing Metro. The tickets, which are 97% recyclable and fully compliant with the Restriction of the Use of Certain Hazardous Substances (RoHS) standard, are more eco-friendly than those produced using traditional methods (Science China, 2013).

Policy settings in China on nanotechnology

To support nanotechnology's development and industrial use, Chapter 4, on nanotechnology and future production, suggests that policy should support institutional

collaboration and develop multidisciplinary networks, particularly collaborations on nanotechnology R&D infrastructures. Governments should also support innovation and commercialisation in small companies, as well as developing transparent and timely guidelines for assessing the risk of nanotechnology-enabled products.

Chapter 6 draws attention to related policy issues raised by developments in the area of new materials, suggesting that governments should monitor possible concerns raised by new materials (such as the possibility of new cybersecurity risks raised by materials created using simulation techniques), and ensure effective policy in a variety of areas that are often important for pre-existing reasons (frequently relating to the science-industry interface and such issues as open data, open science and the quality of the IP regime). Support for interdisciplinary research and education may also be necessary.

International co-operation in nanotechnology was identified as key in the 12th FYP for nanotechnology. From 2000-09 there was an almost ten-fold increase of co-authored papers between China and the United States (from 126 to 1 238 papers). In 2012, the China-Finland Nano Innovation Centre was established in the Nanopolis in Suzhou City. An international conference on nanoscience and nanotechnology has been held biannually since 2005, with the most recent meeting, in 2015, attracting over 1 300 participants from over 40 countries and regions. However, the share of co-authored nanotechnology papers is still below the share of internationally co-authored papers in all fields of science in China.

A National Steering Committee for Nanoscience and Nanotechnology was created to co-ordinate key government departments, funding agencies and research institutes. Nanotechnology was listed as a key technology in China's mid- and long-term science and technology (S&T) development plan (2006-20). Nanotechnology has subsequently received significant funding from all major Chinese funding agencies. In 2016, the Ministry of Science and Technology invested over CNY 600 million (USD 87 million) in nanotechnology research.

SMEs working with nanotechnology can apply for financing from the national SME technology innovation fund, as well as general tax refund and procurement support. A national initiative to open publicly funded key research infrastructures and equipment to the public (including universities, companies and social research organisations) began in 2015. Detailed implementation policies are yet to follow.

In China, new materials have received support in both the 12th and 13th FYPs for S&T. In the 13th FYP, a long-term project, Innovation 2030, focuses on the production and application of important new materials such as carbon fibre, composites, high-temperature compound metal, and new display materials. The interdisciplinary nature of new materials development is acknowledged in the National Mid- and Long-term Talent Development Plan for New Materials, which aims to train over 1 000 interdisciplinary scientists, engineers and managers by 2020. However, specific policies are not yet evident.

Government strategies and policies

A number of high-level government initiatives have been put in place to promote technology development and the upgrading of manufacturing in China. The overarching government initiatives (and the years of their announcement) include:

- the Guidelines on National Medium- and Long-term Program for Science and Technology Development (2006-20) – 2006

- Decision on Accelerating the Fostering and Development of Emerging Industries of Strategic Importance – 2010
- the 12th FYP for National Economic and Social Development – 2011
- Made in China 2025 – 2015
- Internet Plus – 2015
- the 13th FYP for National Economic and Social Development – 2016.

These initiatives are important as they set key goals, directions, specific priorities and frameworks. Being highly general and concise, they are usually followed by more detailed and implementation-oriented action plans. The plans utilise tools and measures such as government investments, R&D programmes, demonstration projects, tax incentives, financing support and human resources policies.

When viewed chronologically, these initiatives also reflect how priorities have changed over the past decade. The increasing importance of manufacturing upgrading is the most obvious example, comprising just chapters in the earlier initiatives to becoming the major subject of Made in China 2025. At the same time, the focus on enabling technologies, which used to be heavily R&D-oriented, is being progressively oriented to commercialisation and industrial application.

The integration of manufacturing and digital technologies, especially ICT and the Internet, is considered the key driver for upgrading manufacturing, while innovations and developments in strategic priorities, such as biotechnologies, new materials and new forms of energy, provide critical additional impetus.

The government's policy approaches and instruments are also changing. As the enabling technologies move from laboratories to industry, government investments and incentives, which used to be the foremost tools, are giving way to system reform and measures to improve the business environment, with markets expected to play a more prominent role. Policies on international co-operation, open infrastructure and data access, and SMEs, are also gaining in importance.

Local governments have also encouraged manufacturing upgrading. Matching funds, tailored incentive policies and industrial parks are among the measures they use.

Overarching government initiatives

The Guidelines on National Medium- and Long-term Program for Science and Technology Development (2006-20) (hereafter "the Guidelines") emphasise the strategic importance of innovation. The Guidelines seek to support a comprehensive system of implementation by co-ordinating policies on R&D investment, tax incentives, financial support, public procurement, IP and education (Table 12.1).

The Decision on Accelerating the Fostering and Development of Emerging Industries of Strategic Importance (hereafter "the Decision") positions itself as coming at an important moment in the upgrading of China's industrial structure and establishes seven emerging industries of strategic importance.[3] These seven industries are expected to represent around 15% of GDP by 2020. To reach its goals, the Decision tries to combine public support with the market, and promotes the involvement of both large companies and SMEs.

The National FYPs cover every important sector of China's economic and social development, and include a focus on enhancing the core competitiveness of China's industry. Following the 12th FYP more detailed plans have been drafted, including the FYP for Industrial Transformation and Upgrading, the 12th FYP for Emerging Industries of Strategic Importance and the 12th FYP for Science and Technology.

Table 12.1. **The implementation system for the Guidelines**

Policy target	Institutions and measures
R&D investments	Funding management policies for national high-tech, basic research, and enabling technologies programmes; policies for R&D for public welfare.
Tax	Import tax redemption for equipment for R&D and teaching; policies for start-ups; tax incentives for corporate R&D.
Finance	SME credit guarantee; investment fund for S&T in SMEs; export credit insurance for high-tech companies; financing for key national R&D projects from business banks.
Public procurement	Public procurement management policies for S&T products.
Technology acquisition	List of technologies encouraged for acquisition.
Human resources	Attracting overseas talent; guiding opinions for employment in R&D institutes; human resources policies in national R&D projects; 11th FYP for post-doctorates.
Intellectual property	National programme to support key technology standards and application; opinions to strengthen public IPR services.
Education	National key disciplines; government overseas scholarship; part-work, part-study education in vocational colleges; open universities and R&D institute.
Innovation platforms	National engineering research centre; national engineering laboratories; state certified corporate R&D centre.

Source: Author's analysis.

Made in China 2025 is a milestone in the sense that it is the first of a series of national ten-year strategic initiatives covering the long-term comprehensive development of China's manufacturing industry. Made in China 2025 has established indicators for industry on innovation, quality, digitalisation and greenness. For example, by 2025, the percentage of R&D spending relative to manufacturing sales is targeted to reach 1.68%; labour productivity is expected to increase by 7.5% annually to 2020, and thereafter by 6.5% to 2025; broadband coverage should rise from 50% in 2015 to 82% in 2025; and energy consumption per unit of added value should fall by 34% by 2025 (Box 12.3).

Until now, implementation has focused on technologies, and has taken the form of central government funding for projects. The government established a CNY 20 billion (USD 2.9 billion) Modern Manufacturing Industry Investment Fund, CNY 6 billion of which comes from the government budget. Besides demonstrational pilot projects, the central government has also started a scheme of experimental cities, under Made in China 2025, in which selected cities are encouraged to identify and develop their comparative advantages in manufacturing. Ningbo and Wuhan are among the first cities selected (He, 2016). However, the paths and directions of Made in China 2025 have raised demand for a more comprehensive approach to implementation, going beyond the particular needs of individual technologies.

Published two months after Made in China 2025, the Internet Plus initiative seeks to better integrate the Internet with industry. Internet Plus promotes digitalisation in 11 sectors,[4] and aims by 2025 to see China with an interconnected service-oriented industrial ecosystem. In manufacturing, integrating the Internet means first developing so-called "intelligent factories" by promoting cloud computing, the IoT, industrial robotics and additive manufacturing. Large-scale customised manufacturing is another priority, in

which the Internet and flexible forms of manufacturing will help to supply more diversified customer needs. A further priority is to increase the services content of manufacturing output.

Box 12.3. **Made in China 2025**

Made in China 2025 identifies nine paths to achieving its ambitions:

1. **Enhancing innovation capability.** The aim is to create a national innovation system in which enterprises lead, government provides services and support for key technology R&D, and research outcomes from academia can be efficiently commercialised.
2. **Promoting digitalisation.** Digitalised manufacturing is the aim, and this covers not only equipment, such as computer numerical control machine tools and robotics, but also intelligent manufacturing processes and related infrastructures.
3. **Focusing on the basics.** Four "basics", as they are called in Made in China 2025, are: basic components, basic processing technologies, basic materials, and basic industrial services.
4. **Boosting quality and building brands.** Quality management, inspection and standards will be introduced to address quality issues. Also addressed are efforts to raise awareness of branding and support to agencies for brand management and marketing.
5. **Making manufacturing greener.** This consists of applying green technologies to traditional manufacturing sectors while developing low-carbon industries such as new materials and biotechnology, promoting resource recycling, creating green supply chains and logistics, and reinforcing greener standards and environmental inspections.
6. **Targeting priority technologies and products.** These priorities include ICTs, numerical control tools and robotics, aerospace equipment, ocean engineering equipment and high-tech ships, railway equipment, energy-saving vehicles, power equipment, agricultural machinery, new materials, biological medicine and medical devices.
7. **Restructuring industry.** This path aims to deal with applications of new technologies in enterprises, overcapacity, co-ordination between large enterprises and SMEs, and industrial planning at regional level.
8. **Developing manufacturing as a service and services for manufacturing.** This path aims to help manufacturing extend the value chain and develop and sell both products and services. Services for manufacturing range from logistics and human resources to IP services and after-sales services. Services for adopting ICTs and mobile Internet business are emphasised.
9. **Opening for international co-operation.** This path seeks to help Chinese companies invest and do business abroad, while attracting to China more foreign investments in high-tech industries and global research centres.

For these nine paths, Made in China 2025 identifies eight directions for implementation. These relate to system reform, fair market competition, finance, tax, human resources, SMEs, international openness, and co-ordination mechanisms. A technology roadmap for the priority technologies and products was published in October 2015. In August 2016, Implementation Guidelines for Five Key Projects (the first implementation policies for Made in China 2025) were issued to start projects for innovation centres, intelligent manufacturing, industry basics, green manufacturing and high-end equipment (addressing paths 1, 2, 3, 5 and 6, respectively).

Internet Plus is implementation-oriented. Each priority has a designated government department responsible for follow-up. But Internet Plus does not rely heavily on government

investments. Emphasis is laid on better public infrastructures, capacity building for innovation, and a more flexible regulatory environment. Openness is also emphasised, with goals established to advance open-source communities, open data, and open infrastructures and facilities.

Complementary measures and policies

Besides government-funded programmes, which are the key measure for implementing the initiatives described above, China has also introduced complementary policies that address systemic reform, finance and tax, IP and human resources. These are briefly described here.

Systemic reform

The government's role is increasingly shifting to strategic planning, policy implementation and improvement of public services. A major reduction of items requiring government administrative approval started in 2013. Over 700 administrative approval items are reported to have been cancelled or handed down to lower tiers of government, many of which are approvals for industrial investments (State Council, 2016). To accelerate administrative simplification, the government is resorting to a "negative list" approach for sectors and economic activities. Other than the listed sectors, the rest, including new sectors and businesses, such as myriad forms of Internet financing and shared-economy ventures, can proceed without going through governmental approval procedures (State Council, 2015a).

Industry has long been promoted as the leading force in technological innovation. To this end, many national R&D programmes are designed to be led by industry. Industrial laboratories and technology centres are eligible for tax incentives and exemptions. Technological innovation is also used as a performance indicator for state-owned enterprises. There is also a growing focus on enabling and promoting technological upgrading and innovation in SMEs, along with better framework conditions, such as access to loans.

The Mass Innovation and Entrepreneurship initiative marks a recent shift in China's innovation policy, towards grassroots innovation and mass entrepreneurship. This initiative entails a significant change from "picking winners" towards more general forms of support for entrepreneurship and innovation (Liu et al., 2017). Policies are also being tailored to the needs of different types of entrepreneur. For example, researchers will be given three years to develop their research into a business while their jobs are preserved in universities or research institutes.

Government is also investing in the infrastructures needed to use new technologies, especially in the fields of ICT and new energy sources. National standards and labels, such as the National Energy Label, have also been created to encourage and guide consumer choices.

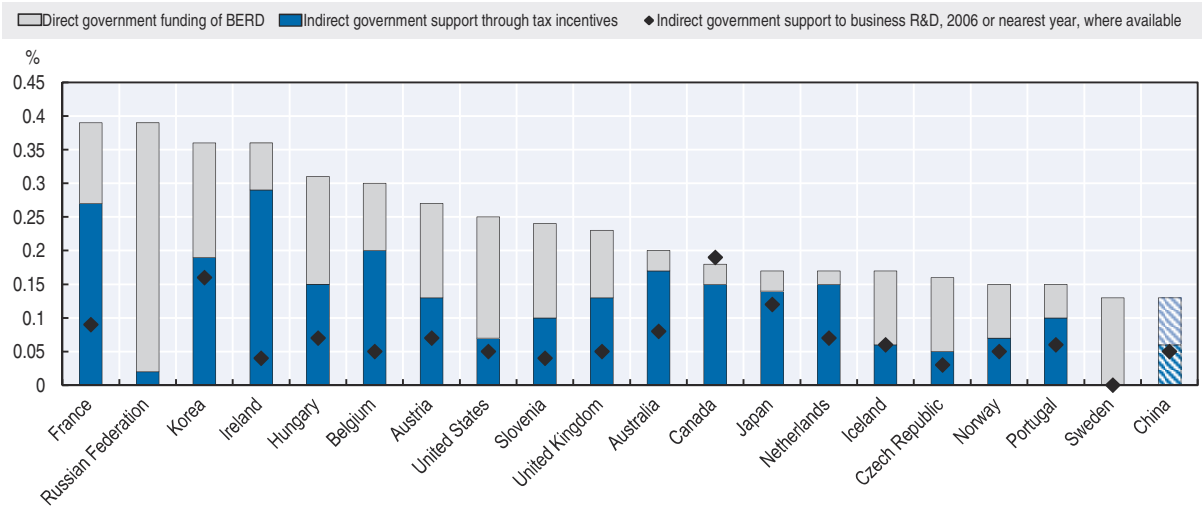
Efforts have likewise been made to strengthen an integrated national market by eliminating incompatible and overlapping regional policies. Other systemic reforms have also been implemented to promote autonomy in research institutes, academia-industry collaboration, regional innovation and the reform of state-owned enterprises.

Finance and tax

Financial support and tax are used to guide private investments and encourage R&D in priority areas. Central government financing is increasingly used to help mobilise resources

from regional governments and private actors, and is changing in form from direct subsidies for buying hardware to performance-based incentives. On tax incentives, the government recently modified eligibility criteria and strengthened supervision, with the goal of increasing policy effectiveness and efficiency. In 2013, China, together with the United States and France, provided the largest absolute volume of tax support for R&D (Figure 12.7).

Figure 12.7. **Direct government funding of business R&D and tax incentives for R&D, 2014 (as a percentage of GDP)**



Note: Data on China refer to 2009 and 2013. For other country specific notes see sources.
Sources: OECD (2017b), *R&D Tax Incentive Indicators*, *http://oe.cd/rdtax* (accessed February 2017); OECD (2017c), *Main Science and Technology Indicators*, *http://oe.cd/msti* (accessed February 2017).

StatLink http://dx.doi.org/10.1787/888933473941

Since 2006, 150% of the costs of technological innovation and of R&D have been deducted from the calculation of corporate income tax. In 2014, total deducted corporate income taxes reached CNY 237 billion (State Administration of Taxation, 2015). In 2015, this policy was widened, to be more accessible to SMEs. A 15% rate of corporate income tax is applied to high-tech enterprises in national high-tech industrial parks (the standard rate of corporate income tax is 25%), with tax exemption for the first two years (Ministry of Finance, 2006). Import tax is exempted for articles used in S&T R&D (Ministry of Finance, 2007a). Import tax is also refunded for key components and materials used in manufacturing critical equipment (Ministry of Finance, 2007b). Incentives also include exemption of value-added tax for technology transfer (introduced in 2010) (Ministry of Finance, 2010), and accelerated depreciation of fixed assets in industries including biomedicine and ICT (in 2014) (Ministry of Finance, 2014).

With respect to equity finance, the first national public Fund of Funds (FoF) was set up in 2006. This FoF helps to establish venture capital funds investing in high-tech start-ups and SMEs. Starting with CNY 100 million in 2007, the FoF reached a capitalisation of CNY 1.3 billion in 2014 (Ministry of Science and Technology, 2014). Following this model, more government venture funds were set up after 2010. Some of these funds aim to promote technology transfer and commercialisation (Box 12.4), while others support emerging industries, especially in ICT, biotechnology, advanced manufacturing and new materials. In 2015, a CNY 40 billion government venture fund for emerging industries was founded. This fund will introduce further market-based management mechanisms and give fund managers more autonomy (State Council, 2015c).

Box 12.4. **National Fund for Technology Transfer and Commercialization**

Established in 2014, the National Fund for Technology Transfer and Commercialization (NFTTC) aims to promote research transfer and commercialisation, especially for research projects supported by government investments. In 2015, it invested around CNY 1 billion (USD 145 million) in setting up three venture capital funds with a total capital of CNY 4.2 billion (USD 610 million).The NFTTC has four key features:

- A national database that includes all outcomes and findings from the research projects.
- A venture capital function. NFTTC sets up a venture capital fund, in partnership with selected investment agencies. The agencies will invest in transferring and commercialising technologies in the database.
- Loan risk compensation for banks. Compensation not exceeding 2% of the loan will be available to banks that support SMEs engaged in transferring or commercialising technologies.
- Performance incentives. A one-time incentive would be available for enterprises, research institutes, higher education institutions or agencies that have outstanding performance.

Large items of technological equipment developed by Chinese manufactures usually need time to build user trust. After Made in China 2025, a pilot programme was set up to provide government insurance subsidies for manufacturers. If manufacturers can reach a deal with insurance companies and sell equipment to customers (the beneficiaries of the insurance), 80% of the cost of insurance will be subsidised for the initial sale. A guiding list was issued in 2015. The Harbin Y-12 turboprop utility aircraft is among first products to be insured in this way.

Intellectual property (IP)

To co-ordinate China's IP strategy with the major initiatives described above, policies have been adopted to address IP application, services and protection. This is occurring in a context of rapidly growing and subsidised patenting, but low patent quality overall, a significant incidence of infringement and a widespread perception in business that patents do not properly protect innovation (OECD, 2017a).

A list of key ICT technologies and products in the information industry has been issued to guide and encourage domestic IP development (Ministry of Science and Technology, 2007). For IP issues in strategic emerging industries, policies have sought to increase IP quality by issuing national guidelines for IP assessment and facilitating IP application through fast-track procedures (State Council, 2012). Measures have also been designed to develop the potential of IP-based business financing, such as IP-backed loans (China Banking Regulatory Commission, 2013). Domestic enterprises and research institutes are likewise encouraged to develop IP overseas.

Since the release of Made in China 2025, pilot projects for industrial patent consultancy have been initiated by the State Intellectual Property Office (State Intellectual Property Office, 2015). These projects provide IP analysis and strategic recommendations in certain industries. A first series of projects has been undertaken in nanomanufacturing, mobile Internet and super-hard materials.

Measures will also be taken to implement more strict protection of IP rights by building a more streamlined and co-ordinated national IP service, management and

enforcement system (State Council, 2015b). Strengthened IP protection is being planned in new fields such as big data, crowd sourcing and crowd funding.

Human resources

"Talent is the foremost resource for China's social and economic development," according to the document "Outline of National Medium-and Long-term Program for Talent Development (2010-20)". As China's first long-term talent development initiative, the outline aims to raise the percentage of highly skilled workers to 28% and the ratio of human capital investment to GDP to 15% by 2020. Among others, equipment manufacturing, ICT, biotechnology and new materials, are specified as priority areas for skills development (State Council, 2010).

To develop skills in these priority sectors, sub-initiatives will enhance the capabilities of business managers and highly skilled workers. In addition, 12 national human resource development projects are being implemented, streaming national investments to the training of young researchers and technicians, to the use of overseas talent, and to skills development among managers and technicians.

Made in China 2025 has emphasised the importance of a comprehensive skills system in areas ranging from R&D, research translation and application, to production and management. A growing number of general undergraduate colleges are being transformed into vocational colleges to strengthen vocational and continuing education. Pilot projects for modern apprenticeships are also being developed.

As a response to Made in China 2025 and Internet Plus, modifications have been made to the National Catalogue of Disciplines and Specialties for Vocational and Technical College Education (which serves as the guideline for course setting). The modifications include new disciplines such as industrial robotics, IoT engineering, 3D printing for aviation, cloud computing and big data. Further educational initiatives are also under way. For example, while ICTs have long been integrated in primary and middle schools, a national programme for teaching robotics is now under consideration (Ren, 2016).

Besides basic education, measures will be taken to provide more overseas training opportunities and attract skilled individuals from overseas. To these ends, the Talent Development Programme for Manufacturing Industry (2016-20) is being developed by the Ministry of Education. Policies are also being tailored to the needs of researchers and academics. For example, their jobs will be preserved in universities or research institutes for up to three years if they develop their research into a business. Services and incubators will be provided in universities to support student start-ups, which will also enjoy preferential tax status.

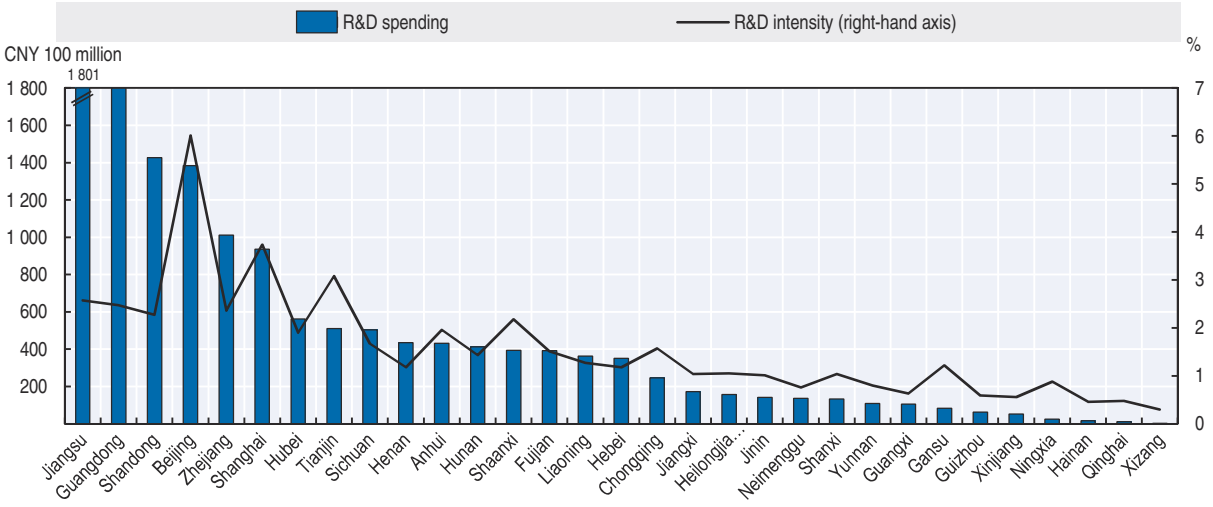
Regional initiatives

China's regions vary greatly in terms of industrial development (Figure 12.8). Made in China 2025 became one of the most frequently mentioned initiatives in regional government reports in 2016, as provinces began to follow up with their own initiatives (Ma, 2016). This also raises challenges of overlapping investments and competition among regions, and calls for better co-ordination and governance at both central and regional levels.

Some regions, especially the more developed coastal and eastern provinces, have initiatives to develop industries in robotics, the IoT and drones, such as the Robots Replace Humans programmes. Other regions focus on upgrading existing industries with new

technologies. For example, Hebei province, challenged by overcapacity in steel, cement and glass production, aims to advance industry reform and green growth through Made in China 2025.

Figure 12.8. **R&D spending across regions in China 2015**



Source: Ministry of Science and Technology (2015c), "2015年全国科技经费投入统计公报" [R&D expenditure 2015], *www.most.gov.cn/kjbgz/201611/P020161118627899534071.doc.*

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New technologies have also provided opportunities for regions in inner China. For example, Sichuan is among the first provinces to create a long-term Roadmap for Additive Manufacturing (2014-23), and has set specific priorities for 3D printing in the aviation and precision machinery industries (Wu, 2014). Guizhou, a less-developed province in mid-western China, aims to become the data centre of China and has issued China's first regional regulation on big data.

China presently has over 145 national high-tech parks. These are considered important for regional governments in promoting technological advances. Besides high-tech parks, Smart City is another government initiative taken up by many Chinese cities. By 2015 there were around 300 pilot Smart City projects in China (Ministry of Housing and Urban-Rural Development, 2015). These aim to apply the IoT, big data, cloud computing and mobile Internet to infrastructure, public governance, transportation, health care and industrial production.

Key challenges and policy considerations

Upgrading manufacturing in China faces complex challenges. The upgrading process is not just about developing the latest technologies. It also requires a greatly increased use of those technologies, as well as upgrading and restructuring a vast productive capacity that still operates at the level of industry 2.0 (or even, in many cases, 1.0) (Yang Jun, 2015). Major challenges exist not only in increasing government investment in science, research and innovation, but also commercialising research and encouraging proactive private sector innovation. Hardware must be enhanced, such as ICT infrastructure, along with software and skills. The challenge also spans central and local governments, as well as research institutes and universities, SOEs and SMEs. While policies and programmes are

promoting the technologies necessary to upgrade manufacturing, policy also needs to cope with a range of related developments and impacts, such as the growing importance of cyber security, and disruption in the labour market. At the same time, attention must be paid to issues of governance, such as co-ordination among government departments and between central and regional governments.

Polarisation of technology capabilities

Chinese manufacturing is highly polarised. Examples have been given in this paper of cutting-edge technological development and use among Chinese firms. But in many sectors extensive gaps exist in basic manufacturing capabilities, such as the mastery of key processing technologies and the ability to produce necessary materials. Indeed, most of Chinese manufacturing lags in terms of management and digital capabilities. In the words of Miao Wei, Minister for Industry and Information Technology, "Chinese manufacturing is still at a stage where industry 2.0 and 3.0 is happening together and has to develop to simultaneously finalise industry 2.0, popularise 3.0 and demonstrate 4.0." (Feng B., 2015) Firm surveys confirm this observation (Figure 12.2). Such uneven development, combined with an industry structure in which resource and energy-intensive sectors are still large, creates complex challenges.

At the higher end of manufacturing, challenges include a heavy reliance on imports of core capabilities, such as advanced equipment, system software and critical components such as servomotors for IRs and certain high-quality steel products (Box 12.5); insufficient investment from research institutes in basic research and a low intensity of business spending on R&D (relative to sales, for example); and, a lack of synergy between research institutes and industry, resulting in inefficient technology commercialisation. In the mid-range of manufacturing capabilities, challenges include a need to raise product quality; overall inefficiency; weak brands; and a need for further technological innovation so as to climb value chains. Challenges are particularly large and complex for upgrading in resource and energy-intensive sectors, which is also intertwined with issues of overcapacity, low levels of industrial sophistication and environmental pollution.

Box 12.5. **A ballpoint pen Made in China**

In a recent meeting to address overcapacity in the steel and coal industries, held in Taiyuan, capital city of Shanxi province, a region rich in coal but now facing challenges of stalled development, the Chinese Premier Li Keqiang observed that despite great overcapacity in steel production China still needs to import certain high-quality steel products, including those used to produce the tips of ballpoint pens.

This problem was observed back in 2011 by Wan Gang, the Chinese Minister for science and technology, who pointed out that for the 38 billion pens made in China 90% of ballpoint pen tips are imported. In 2012, a national research project on key materials and equipment in pen-making was initiated. CNY 60 million was invested by the government, with twice this amount invested by the principal investigators, making it the largest research project in China's pen-making industry to date. This project studied three sub-themes, around ink, tips and tip-ink matching. Three companies – one SOE and two private companies – took part. The project was finalised in 2015, with a successful demonstration in producing 1 000 metric tonnes of steel per year for the tips of ballpoint pens (Ministry of Science and Technology, 2015b).

Box 12.5. **A ballpoint pen Made in China** *(cont.)*

Premier Li's observation, when combined with this project, is a reflection of the polarisation of Chinese manufacturing. It also illustrates the government's strategy to address this problem, with industry taking the lead in both R&D and investment, while government acts in a support role.

Making markets work for industrial upgrading

Improving the efficiency with which human and financial resources are allocated is essential. Aligning framework policies that promote product market competition, reduce rigidities in labour markets, and remove disincentives for firm exit and barriers to growth for successful firms is critical. Resources used in production need to flow at low cost to firms that can develop and use new technologies effectively. Creating a context of efficient resource allocation will also help firms invest in the business processes, skills and other intangible assets which can amplify the impacts of digital and other technologies (OECD, 2013). However, excessive administration and direct public intervention have often damaged market mechanisms. Some policies have hindered competition by giving targeted support for specific enterprises, technologies and products. Public intervention in how businesses are managed has also happened from time to time (Zhao, 2016). In ways detrimental to competition, policies have sometimes varied according to enterprise ownership and size. While barriers to business creation have been reduced in recent years, significant scope remains to enable entrepreneurship (OECD, 2017a).

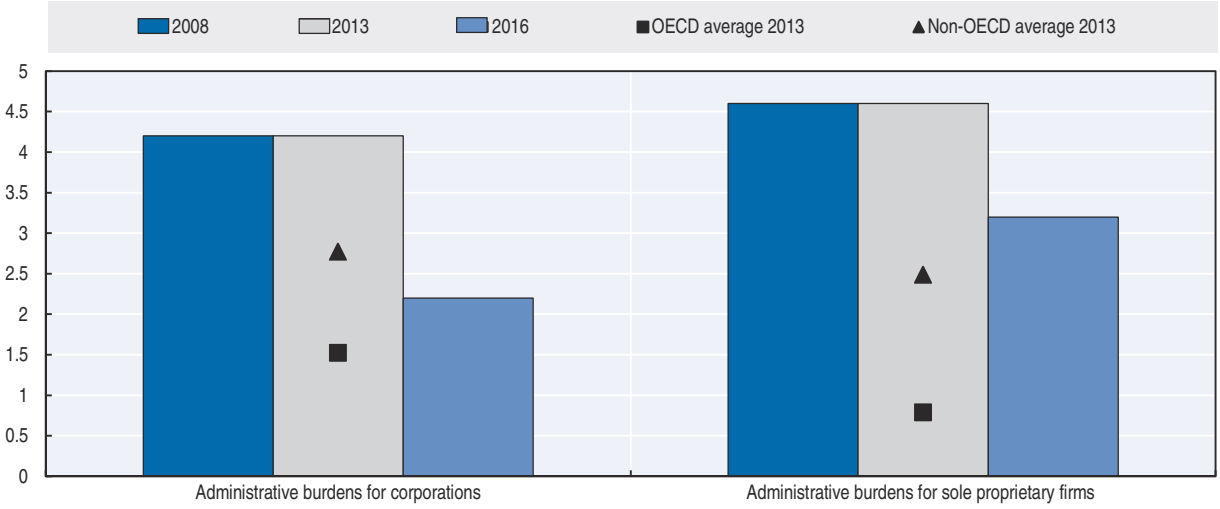
In part because of the sorts of policy weaknesses outlined above, industrial policy in China has yielded mixed results. For example, industrial policy for the automobile industry failed to encourage significant domestic private capital investment (Development Research Centre, 2011). On the contrary, industrial policy hindered private investment in the automobile industry and led to a small, scattered and weak sector with little innovation activity. In the automotive sector, China's brands are generally weak, the key technical areas lack independent IP, R&D personnel are scarce and as a result R&D is inadequate (Jiang, 2016).

The easing of administrative burdens on start-ups and streamlining of procedures have reduced overall barriers to entrepreneurship (Figure 12.9). Nevertheless, there is ample room to make the business environment more entrepreneurship-friendly. For the market to function to its full potential, rigid economic regulations should be loosened, discriminatory policies abolished and entry and exit barriers reduced (including making bankruptcy procedures quicker and clearer) (OECD, 2017a). These steps will also create a fairer environment for all actors. At the same time, it is important to take measures that prevent market leaders taking advantage of their technology or market power in order to set barriers for newcomers. There is also a need to fully assess the impacts of present tax policy in the light of the ambitions of Made in China 2025 and Internet Plus, and to simplify tax procedures (State Administration of Taxation, 2016). Measures may also be needed to build diversified financial services able to support firms working in next production revolution-related fields (particularly with respect to mid- to long-term loans and equity finance) (People's Bank of China, 2016). There is also a need to improve patent quality (from both businesses and universities), in part by streamlining the system of patent subsidy, and ensuring effective enforcement of IP rights (especially for smaller enterprises), with fines for violators set at levels which have a deterrent effect (OECD, 2017a). More strategic policies

may also be needed in the area of standards, with current plans for standards development better accounting for the needs of industry (e.g. by developing a system of standards for big data). A more active role in international standard-setting could also be valuable.

Figure 12.9. **Barriers to entrepreneurship**

OECD Product Market Regulation indicator, 2008, 2013 and 2016



Note: The value of the indicator ranges from 0 to 6, with 6 being the most restrictive.
Source: OECD (2017d), *Product Market Regulation* database (accessed February 2017).

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"Zombie companies" is a term used to describe Chinese companies, often in sectors with large overcapacity, with large debts, a history of losses and which are only sustained by bank loans or government support. Such companies produce continuously, regardless of increasing costs and falling prices. These companies are not only unable to upgrade by themselves, they also absorb scarce resources and create fierce competition for companies that invest in new technologies. In February 2016, the State Council published Opinions on Resolving the Overcapacity Problem of the Coal Industry and the Steel Industry. Among measures to close or reduce production, intelligent manufacturing is being promoted in the upgrading of the steel industry to create a new production mode that is more flexible and customised. In this reform, emerging challenges include policy enforcement and how to deal with job losses (an estimated 1.8 million jobs are at risk in this process) (Zhong, 2016).

Improving innovation and innovation policy

The Chinese domestic market is still price-sensitive. Businesses usually achieve lower prices through imitation and lower material quality, or even counterfeiting, which is especially discouraging for companies which might otherwise invest in innovation and technology upgrading. Lower output quality also damages the reputation of Made in China 2025 as a whole.

The ballpoint pen story outlined in Box 12.5 also illustrates the challenge of how to provide effective incentives for companies, especially private companies, to engage in technology upgrading and R&D. The efficiency of private sector R&D is low (OECD, 2017a). Many domestic private companies hesitate to apply the latest technologies, either because of the scale of the investments required, or because of uncertainties in technology trends and standards. Compared to research institutes or central SOEs, the private sector's role in

research is also limited. For example, over 70% of nanotechnology patents and 50% of robotics patents are filed by the academic and public sectors (World Intellectual Property Organization, 2015). An efficient commercial translation of research outcomes is needed for these patents. The business sector, both private and public, also tends to spend relatively little on R&D, as a share of revenues, compared to other countries (Table 12.2).

Table 12.2. **R&D intensities of manufacturing and high-tech industries in selected countries (%)**

	China 2012	US 2007	Japan 2008	Germany 2007	France 2006	UK 2006	Korea 2006
Total manufacturing	1.1	3.4	3.4	2.3	2.5	2.4	1.9
High-tech industries	1.8	16.9	10.5	6.9	7.7	11.1	5.9

Note: China's R&D intensity is calculated as R&D expenditure as a percentage of revenue from the principal business.
Source: Ministry of Science and Technology (2013), *China High-Tech Industry Data Book*, based on data from the National Bureau of Statistics' *China Statistics Yearbook on High Technology Industry* (2013) and the OECD STAN database on R&D intensity of manufacturing sectors 1995-09 (*http://stats.oecd.org/Index.aspx?DataSetCode=STANI4#*).

Even for leading innovators, challenges arise when they try to bring new technologies into business. In the 2016 National People's Congress (NPC) and National People's Congress and Chinese People's Political Consultative Conference (CPPCC) sessions – China's highest national consultation mechanism, in which chief executive officers (CEOs) are called to give suggestions and recommendations for policy making – many proposals were made relating to new technologies. These mostly focused on the need for technology-related standards, smarter government regulation for new forms of business generated by new technologies (e.g. ride-hailing services by Uber and Didi became legal in July 2016), and amendments to existing laws and regulations to better encourage individual innovation.

Globalisation also creates new opportunities and challenges for Chinese manufacturing. For example, Chinese companies increasingly consider mergers and acquisitions as a path to upgrading (Deloitte and CMIF, 2015). At present, major Chinese overseas investments are concentrated in industries such as mining, oil and gas. But potential also exists in fields of ICT, high-end equipment manufacturing and new materials. The largest Chinese outbound mergers and acquisition (M&A) deal in 2015 – ChemChina's acquisition of Italian tyre maker Pirelli – will enable ChemChina to manufacture premium tyres and move up the value chain (KPMG, 2016). However, weak operational capabilities, such as inadequate human resources and understanding of local regulations, could hinder overseas expansion. According to Bloomberg, USD 47.5 billion in acquisition attempts by Chinese companies failed in 2015 (Gopalan and Langner, 2016). As China's overseas M&A activity targets more advanced sectors, the challenges may grow. For example, in January, Go Scale, a Chinese private equity firm, was blocked from buying Philips' lighting business (Lumileds) by the United States, citing security grounds (Sterling, 2016). The sale of Aixtron, a German chip maker, to Fujian Grand Chip Investment Fund was also blocked (Chazan, 2016).

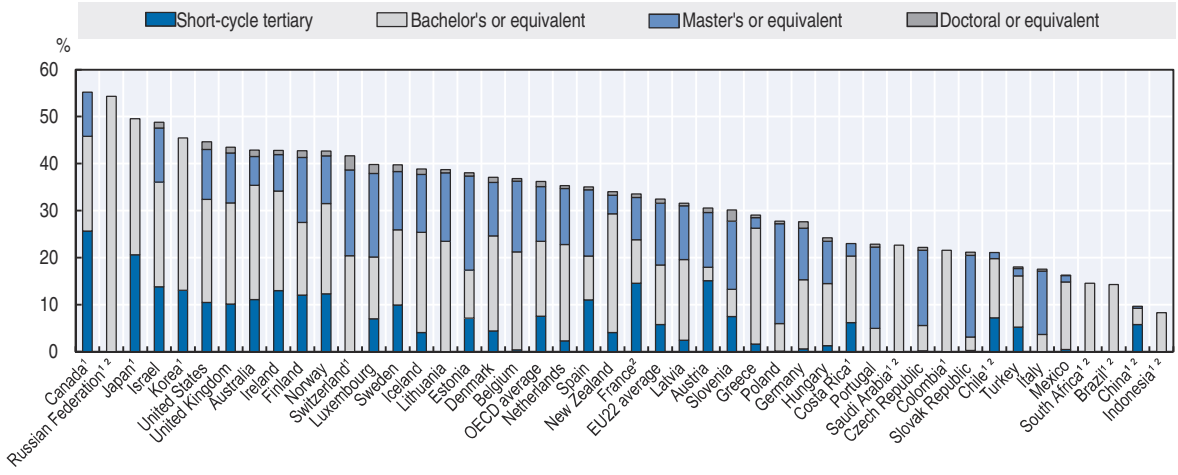
OECD (2017a) suggests reforms in aspects of policy which affect innovation. Various of these – such as reducing the patent subsidy – have already been referenced. Other relevant steps are also needed to address low rates of inter-firm collaboration on innovation, and low collaborative innovation between firms and research institutions; ensure consistent treatment across regions in how support for new and high-technology firms is allocated; update the services offered by high-tech parks; and, improve screening procedures in order to make support for R&D more efficient.

Employment and skills

Across the Chinese labour market, from immigrant workers to engineers and managers, the impacts of upgrading in manufacturing are being felt. Xin Changxing, vice minister at the Ministry of Human Resources and Social Security, asserted early in 2013 that structural unemployment is likely to increase (Wang, 2013). The issue has two parts: a lack of workers with suitable skills, and a lack of jobs for the unskilled. The number of migrant workers in China reached 166 million in 2013, 60% of whom are under 30 and have an average educational attainment of 9.8 years (it takes 9 years to finish junior middle school). Migrant workers' wages increased 12% a year during the period 2011-13 (Cai and Zhang, 2015). Against this background, the Robots Replace Humans initiatives in regional provinces are a response to the lack of suitable labour and the escalating costs of better educated workers (Bai, 2014).

As ICTs and other technologies become more integrated in manufacturing, demand for human resources with interdisciplinary capabilities and skills is forecast to rise. Data from the OECD's 2015 Programme for International Student Assessment (PISA) show that China's students rank among the top ten globally in science and maths. But in terms of skills, programming as well as management and other soft skills were found to be scarce (OECD, 2015a). More generally, there is ample room to increase overall levels of education in China (Figure 12.10). Industrial upgrading also creates new demands on senior management's understanding of technology and its implications for business development. Continuing education and training is important for upgrading this segment of management.

Figure 12.10. **Percentage of 25-64 year-olds with tertiary education, by level of tertiary education (2015)**



1. Refer to the source table for more details.
2. The reference year differs from 2015 (refer to the source table for more details).

Notes: Countries are ranked in descending order of the percentage of 25-64 year-olds with tertiary education, regardless of the level of tertiary attainment. See Annex 3 of the source for additional notes.

Source: OECD (2016a), *Education at a Glance: OECD Indicators*, *http://dx.doi.org/10.1787/888933396600*.

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Meanwhile, new education, health care and social security policies are called for, to address not only the needs of internal migrant workers, but also the needs of a new wave of self-employed entrepreneurs. Expansion of the numbers of self-employed is expected following the national Massive Entrepreneurship and Innovation initiatives that encourage citizens, especially researchers and college students, to start their own business.

Infrastructure

China scored 4.2 in the Network Readiness Index, ranking 62nd among the 143 countries covered (Dutta, Geiger and Lanvin, 2015). The relatively higher price and lower speed of China's Internet have been openly criticised by Premier Li Keqiang, and have room to improve. Major gaps in infrastructure capacity also exist among different regions and manufacturing sectors (Ministry of Industry and Information Technology, 2015a). New industrial infrastructure, such as distributed energy systems, IoT, mobile Internet, industry cloud and industrial big data, is important for the next generation of production and is yet to be fully developed.

Cybersecurity

China ranked 14th of 29 countries in the 2015 Global Cybersecurity Index prepared by the International Telecommunication Union. The average number of detected information security incidents in China over the 12 months before December 2015 reached 1 245, a 417% rise on the previous year (PwC, 2015). As ICT becomes critical to key industries, and the IoT has greatly expanded the number and variety of connected devices, cybersecurity challenges and their financial implications increase. Hangzhou Xiongmai Technology, a manufacturer of Internet-connected cameras, recalled over 10 000 webcams after the large-scale Dyn attack in the United States, which disrupted major Internet services such as Twitter, Paypal and Amazon. The devices may have been hijacked by malware for Internet attacks (Hern, 2016). In this connection, China's first law on national cybersecurity was approved by the Standing Committee of the NPC in November 2016. China may need to strengthen long-term studies relevant to cybersecurity and biotechnology laws and regulations, especially with regard to business confidentiality, privacy and IP (Development Research Centre, 2016).

Governance

As summarised above, China has begun many initiatives to upgrade manufacturing. However, there is scope for optimisation. On the one hand, despite the breadth of recent government initiatives, policy might not be systematic enough. In any modern economy, the policies that affect production are many. They touch on issues ranging from scientific discovery to technology development, technology transfer and internationalisation. Policy must also involve and influence enterprises, universities, research institutions, financial institutions, central government, local government and other bodies. Accordingly, the policy instruments used are scattered across different parts of government.

Nevertheless, the relevant policies in China could be better systematised. The overarching initiatives do not yet cover the whole value chain, all the actors involved, or the different spatial aspects of the issue. Government departments often act in isolation. For example, the management of policy towards biological medicine belongs to different departments. Some of these focus on the social aspect of policy (health). Others focus on the economic dimension of policy (industry). These goals can involve trade-offs, which means that a higher-level body, such as the State Council, should make and co-ordinate overall policy. Similarly, the objectives of fiscal and taxation policy, trade policy, financial policy, investment policy, industrial policy, competition policy, innovation policy, education policy, social security policy and regional policy vary. Complementary policy design or co-ordination has not yet occurred in the context of Industry 4.0.

In a related way, the problem of duplicated construction is serious. For example, by the end of 2012, in 31 Chinese provinces, cities and autonomous regions preferential support

had been given to develop the photovoltaics sector. Some 300 cities have formulated plans to develop the photovoltaics industry and more than 100 have built infrastructure for this purpose. The photovoltaics industry has received preferential access to land, credit and other production inputs. These incentives have attracted too much capital investment into the industry (Fu, 2014).

Similarly, after the introduction of Made in China 2025, provinces and cities released their own action programmes and plans to develop ten strategic industries. Across the country, border towns and mega-cities have launched robotics, big data and other projects and constructed similar industrial parks. This may well lead to overcapacity and wasteful competition. Indeed, in the past, duplicative actions have led to the waste of construction land, human and other resources. Redundant construction has also brought huge losses for the long-term development of local economies and enterprises. To give an example, Qinhuangdao City in Hebei Province, Guian New District in Guizhou, Chongqing Liangjiang New Area, Lanzhou New Area, Hangzhou and other districts propose to build big-data industry clusters. Among these, Guian New District in Guizhou, Chongqing Liangjiang New Area and Lanzhou New Area treat big data as the city's principal industry and emphasise its development in new city planning (Chen, 2014).

China's three major telecom operators have also constructed large data or cloud computing centres. China Telecom has constructed more than 330 Internet data centres. At present, redundant construction around so-called "cloud computing centres" is significant (Wang, 2016). Some areas have built many data storage centres and ancillary facilities (Ma, 2014). As another example, revitalisation policies brought excessive investment in some heavy industries in 2009 and may be one reason for current excess capacity (Zhao, 2016).

Lastly, from the earlier description of policies towards key technologies, it is evident that a number of gaps exist. For example, with respect to digital technologies, the transfer and translation of research to industry appears to receive little attention; infrastructure readiness is lacking; competition in Internet infrastructure services is weak; the cybersecurity law has raised concerns among foreign companies (especially technology-based companies); and personal privacy protection and digital risks (other than those bearing on national security) seem to receive limited emphasis. The efficiency of some government support is also questionable. Local governments, for example, tend to subsidise the sale of robots instead of investing in robotics R&D. And in biotechnology, issues of biomass sustainability appear not to be addressed by policy; there are no policies for biorefineries; standards development is weak (if existent); and policy implementation varies across regions. And in this, as in many other specific fields, it is rare to see systematic assessments of the outcome of policies.

Notes

1. The IoT market here includes chips and components, equipment, software, systems, telecom and networking services.
2. Including ICT manufacturing, software and IT services.
3. Energy-saving and environment-protection technologies, next-generation ICTs, biotechnology, advanced equipment manufacturing, new sources of energy, new materials, and new energy vehicles.
4. These sectors are: entrepreneurship and innovation, synchronised manufacturing, modern agriculture, intelligent energy, inclusive financing, welfare services, efficient logistics, e-commerce, transportation, green ecology and artificial intelligence (AI).

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The Next Production Revolution

IMPLICATIONS FOR GOVERNMENTS AND BUSINESS

This publication examines the opportunities and challenges, for business and government, associated with technologies bringing about the "next production revolution". These include a variety of digital technologies (e.g. the Internet of Things and advanced robotics), industrial biotechnology, 3D printing, new materials and nanotechnology. Some of these technologies are already used in production, while others will be available in the near future. All are developing rapidly. As these technologies transform 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. The more that governments and firms understand how production could develop in the near future, the better placed they will be to address the risks and reap the benefits.

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