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A review of international approaches to Manufacturing Research

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A review of international approaches to manufacturing research

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These materials will be updated and extended on an ongoing basis. In particular, it is planned to extend the investigation to cover other important and emerging manufacturing economies, for example India, Brazil and South Korea.

Contents

Preface

This review of international approaches to manufacturing research, commissioned by the Engineering and Physical Sciences Research Council, builds on the Institute for Manufacturing's ongoing investigation of manufacturing research structures and practices. The study is intended to inform EPSRC strategies and plans related to manufacturing research and, in particular, to support the development of the 'Manufacturing the Future' theme outlined in the Council's Delivery Plan.

This is an important period of change for manufacturing and it is hoped that this review proves both helpful and timely for the wider UK manufacturing research community. There is renewed interest among policy makers in all countries in the role of manufacturing within national economies, and a consequent focus on the potential of manufacturing research to enhance industrial competitiveness. More particularly, there is significant interest in the potential of research to address critical manufacturing challenges and opportunities driven by: the increasingly complex and globalized nature of industrial systems; the dramatic reduction in manufacturing timescales and acceleration of technological innovation; and the growing need for sustainable, resource-efficient production.

It is hoped that this report will contribute to strengthening the UK discourse on the importance of investment in manufacturing innovation, by framing it within the international context; showing how key competitor nations approach manufacturing research policies, programmes, practices and structures.

There are important differences between the industrial innovation 'ecosystems' of different countries. The different actors (universities, intermediate research institutes, government ministries, R&D agencies, industries, etc) vary significantly in configuration, mission, the scale and scope of their activities, and their interconnectedness. As most policies, programmes and practices are tailored to national innovation systems, it is difficult to 'benchmark' them in order to make definitive judgements about whether they are 'better' than those in the UK. Consequently, we have chosen, instead, to highlight those features of international approaches to manufacturing research which are significantly different from those in the UK and which may offer competitive advantage. In particular, this report focuses on those distinct approaches that have been highlighted by leading international manufacturing research experts and national stakeholders,as identified in national strategies, stakeholder analyses or policy studies.

The innovation systems context is a hugely important consideration when exploring opportunities to transfer or adapt particular manufacturing research practices, programmes or institutional structures for the UK. Consequently, we have endeavoured to provide brief contextual overviews of national policy discourses (on manufacturing and manufacturing R&D) and the different innovation system actors and structures.

This study is based, primarily, on interviews with leading manufacturing research experts, international policy makers, research agency programme directors and other stakeholders in selected important manufacturing nations. In particular, this report contains detailed analysis of approaches to manufacturing research in the USA and Germany (where the manufacturing research systems offer some of the most transferable practices and insights). There are also overviews of the manufacturing research landscapes, priorities and policies in other important manufacturing nations: Japan, Sweden, China and Singapore.

1. Introduction and overview

This study explores international approaches to the support of manufacturing research, the prioritisation of research domains, and practices for translating new knowledge into industry. The report also summarizes the broader national R&D funding and industrial contexts within which the main manufacturing research organizations and funding agencies operate. Special attention is paid to those approaches to manufacturing research which contrast most strongly with those in the UK, and which appear to give international manufacturing research communities (and the industries they support) significant competitive advantage. Key themes identified during this review are listed below.

1.1 Key themes

1. The revitalization of manufacturing research There is renewed focus in many countries on the potential of manufacturing research to enhance industrial competitiveness. This reflects a broader renewal of interest in the role of manufacturing itself within national economies and new challenges and opportunities associated with the changing nature of manufacturing, including the rise of new competitor manufacturing economies, the accelerating pace of technological innovation, and the increasing need and urgency for sustainable manufacturing.
2. The interdependence of manufacturing and innovation There is growing concern that a knowledge economy which loses interaction with its production base may lose the ability to innovate. Without close connection and interaction between the manufacturing research base and both science and technology (S&T) research and real-world manufacturing, countries may not be able to compete in the important new S&T-based industries of the future.
3. Manufacturing research leadership Senior industry-experienced research leaders have the potential to play a key role in enhancing the effectiveness of the manufacturing research base: shaping and informing the research agendas of their institutions; increasing the level of industry engagement (and research funding); and providing invaluable professional management expertise, operational experience and insights from across the industrial value chain.
4. The industrialization of emerging technologies There is growing awareness of the potential of manufacturing engineering researchers to contribute to endeavours addressing the industrialization challenges of novel emerging S&T-based technologies (such as synthetic biology, regenerative medicine and nanotechnologies).
5. Breaking down barriers Many of the most important manufacturing-related research challenges are highly multidisciplinary, not least because of the breadth and complexity of many real-world manufacturing systems. Increasing effort and attention is being paid to research programmes, practices and structures which bring

together groups with the right mix of expertise to tackle such challenges. While this is important in all multidisciplinary research endeavours, there are particular concerns about the 'siloed' nature of many manufacturing research communities (driven by tenure and grant review processes, the poor image of manufacturing, and a trend towards 'engineering science' rather than user-engaged problem-solving).

6. Mapping the future of manufacturing Many international manufacturing R&D communities attach significant value to systematic (and ongoing) exercises to identify future manufacturing innovation needs and challenges, and to match them with science and engineering developments emerging from the research base. National forums, 'white paper' consultations, roadmapping and foresight processes, etc, are used to improve interactions between academia, industry and government – stimulating dialogue and awareness of opportunities and challenges, barriers to the translation of findings, gaps in innovation funding, academic (and industrial) capabilities, and scope for alignment of policies, programmes and strategies.

7. Emerging research domains, challenges and technologies International manufacturing research priorities vary, generally reflecting national industry structures and S&T strengths, but there are important common themes: sustainable, resource-efficient manufacturing; production technologies to exploit the potential of emerging technologies (in particular novel bio- and nano-technologies); leveraging simulation and modelling techniques to address manufacturing challenges; flexible, rapidly responsive production systems for customized manufacturing.

8. The manufacturing leaders of the future: A dominant theme among international manufacturing R&D stakeholders is the role of doctoral engineers in underpinning the competitiveness of their manufacturing industry base. Often cited as the most important output of public investment in manufacturing research, efforts to give the 'next generation of manufacturing leaders' experience and expertise at the frontiers of advanced manufacturing innovation, substantial and varied industry problem-solving experience, and insights into future challenges (and opportunities) facing manufacturing enterprises, are considered critical.

1.2 Report outline

The key themes outlined above and others are discussed in more detail later in this chapter, and are illustrated within particular national contexts in the subsequent case study chapters.

The chapters on the USA and Germany provide substantial case studies of nations with manufacturing research systems that appear to offer some of the most potentially transferable practices and insights. The other country case study chapters give overviews of selected international manufacturing research systems with important competitive strengths: Japan, Sweden, China and Singapore.

The final chapter offers observations on those international approaches to manufacturing research which, we believe, contrast most strongly with those in the UK. In particular, we highlight approaches which appear to give international manufacturing research communities (and the industries they support) competitive advantage. In this context, we also identify certain aspects of practices, policies, or programmes where there may be scope to enhance the competitiveness of UK manufacturing research.

1.3 Innovation systems context: Manufacturing research landscape and semantics

In reviewing international manufacturing research portfolios, practices or programmes, it is critically important to be aware of the national industrial-innovation systems context within which they exist. Different manufacturing R&D system actors (universities, R&D institutes, government ministries, agencies, firms, etc.) vary significantly in configuration, culture and mission, in the scale and scope of their activities, and in the quality and nature of their interconnectedness. This systems perspective is crucial in understanding the effectiveness of particular approaches to manufacturing R&D and in considering the relevance and transferability of particular practices, programmes or institutional structures for the UK.

Furthermore, there are significant variations in how the term 'manufacturing research' is used in different countries. Such semantic differences reflect national industrial strengths and innovation priorities. The perceived boundaries associated with 'manufacturing research' may vary in terms of: relevant academic disciplines, industrial sectors and systems impacted, as well as levels of technological and industrial maturity. There is thus considerable scope for ambiguity and confusion. These variations in terminology and interpretation are discussed in more detail in Appendix 1.

1.4 The revitalization of manufacturing research

There is increasing focus by policymakers in many countries on the potential of manufacturing research to enhance industrial competitiveness. This attention reflects a broader renewal of interest in the role of manufacturing itself – notably its importance as a source of high value jobs within a balanced economy, but also its essential function within a sustainable national innovation system.

The frontiers of manufacturing engineering research are being shaped not only by new science and technology but also by fundamental changes in the nature of manufacturing itself. In particular, there is significant interest in the potential of manufacturing research to address the challenges and opportunities created by: the increasingly complex and globalized nature of manufacturing systems; the dramatic reduction in manufacturing timescales and acceleration of technological innovation; and the growing need for sustainable, resource-efficient production (see below). There is also growing awareness among policymakers of the potential of manufacturing innovation to contribute to tackling social, economic and environmental 'grand challenges', such as healthcare, sustainability, and mobility.

In response to these technological, social and economic challenges, many international policymakers and R&D funders are reviewing their manufacturing research agendas with urgency and purpose. This renewed interest is reflected in a range of national summits, new policy initiatives and emerging strategies. Particular attention is being paid to configuring practices, programmes and institutional structures to bring together the right expertise to address key manufacturing-related R&D challenges.

1.5 The changing landscape of manufacturing and industrial innovation

At the same time as many international policymakers look towards production-based industries to help rebalance their economies, manufacturing itself is undergoing significant changes:

- **Globalisation** International distributed value chains and new dynamic competition from emerging economies are influencing manufacturing research priorities. Leading manufacturing economies are investing considerable effort into understanding how value-add can be organised and pursued within national manufacturing systems to ensure that firms compete effectively in the global economy, including the potential for gaining competitive advantage from new strategies for balancing the distribution of domestic and outsourced production to capture cost savings while retaining core capabilities.
- **Sustainability** There is an increasing acknowledgment that sustainable manufacturing goes beyond the production stage of the value chain; it extends across a product's lifetime and addresses the entire system of integrated components, energy, and transportation required to assemble the final product and deliver it to customers. Consequently, there are significant societal pressures and potential competitive advantage in addressing the sustainability agenda throughout the entire product and production cycle, and manufacturing-consumption system.
- **Manufacturing timescales** Time is an increasingly critical factor in today's manufacturing environment. More efficient and flexible supply chains, technological advances and changing patterns of demand among buyers and customers are driving ever shorter product development cycles and accelerating the delivery of individualized products and value-added services. In this environment there is increasing competitive advantage from highly responsive, distributed production capabilities.
- **Emerging science and technologies** The accelerating pace of S&T innovation is also transforming manufacturing. Advances in information-, nano-, bio- and other technologies are creating opportunities for significant economic and social benefit. There is a growing focus on the potential for manufacturing research to offer competitive industrial advantage (especially to nations with a strong science base) by supporting the translation of novel S&T into new or more effective production technologies, efficient manufacturing processes, or high-value-added products.
- **Emerging industries and the manufacturing base** There is an increasing awareness of the interdependent nature of manufacturing and innovation: a knowledge economy that loses interaction with its production base may lose the ability to innovate. Novel S&T-based products often rely on manufacturing skills and infrastructure. Without close connection between the research base and real-world manufacturing, it may be difficult to innovate and ultimately participate in important emerging S&T-based industries. Manufacturing research offers a potentially important bridge between the S&T base and the manufacturing base.

The changing nature of manufacturing presents significant challenges, but also huge opportunities to gain competitive advantage through industrial innovation. Across all the countries explored for this review, manufacturing research was considered a critical component of efforts to face these challenges. The remainder of this chapter summarizes some of the approaches to identifying research needs and developing research strategies, and identifies some the key manufacturing research challenges and prioritised research domains.

1.6 Evolving national manufacturing innovation needs, strategies and research priorities

Although there is significant agreement between nations on many of the trends and drivers shaping the future of manufacturing (as discussed above) and, indeed, on the critical role of manufacturing-related research in maintaining industrial competitiveness, different countries have adopted a variety of approaches for identifying, prioritising and funding particular manufacturing-related research domains.

Funding agencies and research communities in several countries appear to derive value from forums and/or structured and systematic approaches to identifying future manufacturing industry challenges and innovation needs; matching these with science and engineering (often multidisciplinary) developments emerging from the research base; and designing appropriate funding mechanisms and priorities. Some governments commission substantial studies to explore future challenges facing manufacturing industries and corresponding research and innovation needs. In other countries it is learned societies, national academies and/or industry associations which have taken the lead in building consensus on R&D priorities for national strategy. In addition, some government units or R&D agencies offer a forum for stakeholders to transfer knowledge and share insights into the changing nature of manufacturing and critical S&T developments.

Many manufacturing research stakeholders interviewed during the course of this review highlighted the potential of such systematic, consultative and forward-looking exercises to improve interactions and awareness between academia and industry; as well as with central government and other innovation agencies. In particular, they stimulate dialogue and debate on key issues such as: emerging research opportunities and challenges; barriers to translation of research findings; gaps in innovation funding; mutual awareness of academic and industrial capabilities; and opportunities for alignment of policies and programmes.

1.7 Manufacturing the future: emerging domains, identified challenges and capability needs

The full set of research topics and challenges prioritised by different countries (through processes outlined above) vary in emphasis, investment and specificity. Variations often reflect national science and technology strengths or the interests of dominant manufacturing industries within the economy. There is, however, significant consensus around a number of research challenges and topics. Examples of common manufacturing research priorities or 'hot topic' themes that appear across all the leading manufacturing economies include:

- sustainable, resource-efficient manufacturing
- production technology to exploit the potential of emerging technologies (in particular novel bio- and nano-technologies)
- leveraging simulation and modelling techniques to address manufacturing challenges
- flexible, rapidly responsive production systems for customized manufacturing

Examples of national variations in themes and/or emphases include:

- the US emphasis on next generation materials (and novel materials engineering) for manufacturing
- the Japanese focus on the implications of demographic changes: the prioritisation of research on new production technologies for an aging workforce, and opportunities associated with the manufacture of new products for an aging population
- German efforts related to manufacturing processes that protect products from piracy
- Japan's prioritisation of visualization technologies and integration of other IT systems with production technologies to enhance the competitiveness of manufacturing systems

1.8 Manufacturing research system actors

This report explores international manufacturing research activities analogous to those supported by the EPSRC and, consequently, focuses on research within university departments and centres (and funded by national research councils). The manufacturing innovation systems of different countries vary significantly, however, both in terms of manufacturing R&D funders and of research-performing organizations. Comparable and/or complementary research is performed and supported by a variety of non-university organizations, which vary in mission and structure from country to country. The influence of the different actors on each other is also important, for example, the strategies and scope of some US university manufacturing centres are influenced by research funding opportunities from the Department of Defense, while the manufacturing research activities of some German universities have evolved to complement the activities of local Fraunhofer Institutes (and vice versa).

Stakeholder interviews also highlighted the role of intermediate research and technology organisations (e.g. Fraunhofer Institutes) in strengthening national manufacturing research competitiveness and impact. It was suggested that many such organizations offer manufacturing-related engineering skills, technologies and infrastructure (such as test beds, prototyping facilities and pilot manufacturing) to address research challenges that are beyond the capacity of firms or universities. Access to this infrastructure, as well as other interactions through contract (or collaborative) research help translate and diffuse new manufacturing-related technologies, processes and capabilities throughout the innovation system.

A further theme was the importance of university-based research centre programmes . In particular, it was emphasized that some of the most important emerging manufacturing research challenges are intrinsically multidisciplinary, systems based, and user-challenge driven. Research centre programmes are seen as a way of bringing together a critical mass of diverse expertise to address challenges of a scale and system complexity that individual researchers (from traditional research domains) would not be able to tackle. Centres are seen as a mechanism for increasing interaction and understanding between research communities that might otherwise be 'siloed'.

1.9 Manufacturing leadership

The experience of some international manufacturing research communities suggests that there is significant potential to enhance some university-based manufacturing research by engaging senior industry-experienced research leaders. Such individuals can make an impact, not only by running their own high quality, high impact research programmes, but also – perhaps more importantly – by helping to shape and inform the manufacturing-related research agendas of departments and research centres; increasing levels of industry engagement and funding and using their professional management and operational experience to support complex multi-partner research programmes. For many manufacturing research challenges, industry professionals with appropriate experience across different parts of the manufacturing value chain can be invaluable.

In some countries (notably Germany) most professors of 'production technology' have had significant industrial career experience. Indeed, for several German universities, this is the most common career path route for senior manufacturing research academics. In the US, the proportion of manufacturing research professors with significant industry careers is smaller, but it is striking how many successful manufacturing-related centres have directors with industry experience. Research leaders with significant and broad manufacturing industry experience can also be found embedded in roles such as 'Professor of Practice' or industrial engagement director (of research centres). Perhaps unsurprisingly, the founding directors of many intermediate manufacturing research institutes or production-related centres of national laboratories (e.g. SIMTech in Singapore) had impressive industrial research, manufacturing and management track records in major global corporations.

1.10 Manufacturing leadership of the future

One of the most important themes to emerge during this review was the importance of giving doctoral engineers the skills and experiences to be successful in addressing the challenges and opportunities outlined above. Many stakeholders suggested that this 'next generation of manufacturing leaders' was critical in underpinning the competitiveness of the manufacturing enterprises of national economies. Indeed, many cited doctoral engineers as the most important output of public investment in manufacturing research. The efforts to give PhD students experience and expertise at the frontiers of advanced manufacturing innovation, substantial and varied industry problem-solving experience, and insights into future challenges (and opportunities) facing manufacturing enterprises, are considered critical. In several countries, a particular emphasis was also placed on the importance of producing 'global' manufacturing PhDs – engineers with the skills and experience to compete in complex and globalized industrial systems, where design, production, and distribution operations span international borders.

Manufacturing engineering PhD students in different countries are exposed to different levels of industry engagement. In Germany, for example, production technology doctoral engineering candidates[1] engage in a substantial number and variety of industry problem-solving projects. Huge value is placed on the experience, judgement and decision-making skills developed in this way. Although some of these experiences may not be too different from those gained by the UK's growing pool of EngD students, it should be remembered that the vast majority of German doctoral engineers are trained in this way.

[1] In Germany, a manufacturing engineering doctoral candidate would typically be considered a member of the engineering staff of their institute and almost never a 'student'.

2. United States of America

2.1 Introduction

Despite the rapidly changing nature of global manufacturing, the US remains the world's leading manufacturing research nation. America is home to some of the most important global manufacturing corporations, many of the leading manufacturing and industrial engineering research universities, and a diverse set of federal mission agencies with significant investments in manufacturing-related R&D. The US manufacturing innovation system (funding agencies, corporations, research institutions, etc) differs in important ways from that of the UK, and research topic priorities contain some different emphases. Nevertheless, the US still contains important messages for the UK manufacturing research community and policy makers.

Manufacturing – its economic importance, future challenges, and the role of the research base in supporting its ongoing competitiveness – has received significant attention by US policy makers and other stakeholders over the last year and more. The level of interest and urgency is reflected in, for example: the 'Framework for Revitalizing American Manufacturing' issued by the White House at the end of 2009 and the ongoing analysis of advanced manufacturing by the President's Council of Advisors on Science and Technology, as well as a range of symposia, summits and workshops hosted by federal agencies, learned societies, industry associations and leading manufacturing research universities.

In this chapter we highlight some important aspects of the US approach to manufacturing research, its manufacturing research system, and other features, including:

- **Manufacturing R&D policy discourse** The number of US policy documents, initiatives and summits related to manufacturing research in the past 2–3 years is striking. These reflect concerns at the highest levels about US manufacturing competitiveness and jobs, the interdependence of manufacturing and innovation, and the consequences for US competitiveness in important emerging industries.
- **Manufacturing research challenges and priorities** Recent policy studies, white papers and workshop reports suggest a high degree of consensus on priority manufacturing research challenges and research domains, for example: sustainable manufacturing; leveraging simulation and modelling capabilities; nanomanufacturing; biotech-related manufacturing challenges/biomanufacturing; advanced robotics and 'cyberphysical manufacturing systems'.
- **Manufacturing research institutions** The US is home to many of the world's leading manufacturing research universities, but has relatively few intermediate research institutions addressing manufacturing R&D challenges (cf. Germany's Fraunhofer Institutes, for example). University-based research centres (with close industry partnerships) play an important translational role in connecting academic and industrial efforts to address manufacturing research challenges.

- **Manufacturing research funders** The US has a diverse range of mission agencies which support manufacturing-related research. Key funders of manufacturing research include not only the National Science Foundation, but also the hugely important Department of Defense (DOD), as well as the National Institute for Standards and Technology (NIST) and the Department of Energy (DOE), which runs the US National Laboratories.
- **Emerging industries** Many US manufacturing research stakeholders place relatively greater emphasis on translational research, the importance of manufacturing research in supporting emerging technologies, and multidisciplinary manufacturing-related 'grand challenges' associated with growing new technology-based industries.
- **Systems approaches to manufacturing R&D** There is a growing recognition among many US manufacturing research stakeholders of the importance of systems approaches (and engineering system capabilities and skills) in addressing many of the most important manufacturing research challenges.

2.2 Manufacturing and manufacturing research policy: discourse and debate

In this section, we attempt to reflect the broader themes and challenges that dominate the current manufacturing policy debate, as well as key issues highlighted within the discourse of the manufacturing research community itself.

The level of policy attention and debate related to manufacturing and manufacturing research is evident from the quality and number of recent high level workshops, forums and summits. Some of the dominant policy themes influencing the US manufacturing research agenda to emerge from these activities are highlighted in the following section, including:

- 'revitalising American manufacturing'
- manufacturing, innovation and the 'industrial commons'
- manufacturing and emerging science and technology
- 'real engineering' versus 'engineering science'
- reshaping the image of manufacturing
- sustainable manufacturing and manufacturability of green technologies
- coordination of federal manufacturing research

The high level of policy attention being paid to the manufacturing agenda is illustrated by the fact that the US President's Council of Advisors on Science and Technology (PCAST) is currently charged with analysing 'advanced manufacturing'. The PCAST investigation is focused on support for new manufacturing technologies and addresses a range of issues relevant to this report including the extent to which university research is being fully utilized by industry and the potential to increase the emphasis on translational research. Other relevant themes include: the impact and effectiveness of public–private partnerships to support new manufacturing technologies; mandating budgets specific to manufacturing technology within federal innovation agencies; the role of government–industry–university innovation clusters to support new manufacturing firms; public–private R&D partnerships to address 'horizontal,' cross-cutting technology platforms (e.g., modelling, simulation) beyond the reach of individual firms; and the value of international benchmarking effort to compare US manufacturing infrastructures (i.e. technology platforms). The PCAST study also seeks to explore the potential for establishing a national S&T-based manufacturing strategy as a pillar of US economic policy [PCAST, 2010].

2010 saw a range of workshops, summits and symposia driven by different stakeholders and focused on different aspects of the manufacturing research agenda in the US. Learned societies held events, such as the National Academy of Engineering's National Symposium on 'Engineering to Improve the Operations of Manufacturing Enterprises'. Leading research universities, for example MIT, held events on topics such as 'Manufacturing and Sustainability' or 'The Future of Manufacturing — Advanced Technologies'.

A more recent workshop [NIST, 2011] held at NIST reflects some of the key manufacturing research-related questions and themes of the US debate. The workshop 'Extreme Manufacturing: What are the technology needs for long-term US Manufacturing Competitiveness?' was run by NIST in partnership with DARPA, NSF and NASA, thereby initiating a discussion forum for interagency initiatives. A key aim of the workshop was to identify crosscutting and enabling R&D investments needed by the federal government to build the innovation infrastructure for successful US manufacturing enterprises. It also aimed to begin to develop a long-term vision for manufacturing and to identify the technologies needed to reach this vision as well as the roadblocks to future success.

2.2.1 'Revitalizing American manufacturing' – a national priority

Much of the discourse in the US has focused on the importance of manufacturing to the US economy and the challenges faced by manufacturing industries. For example, the Framework for Revitalizing American Manufacturing, Executive Office of the President [EOP, 2009] identified seven principles to strengthen the US manufacturing base and addressed the importance of investment in the creation of new technologies and practices, with a particular emphasis on 'helping to bring to scale emerging technologies as well as facilitating the diffusion of business practice innovations that can help American manufacturers compete'.

2.2.2 Manufacturing innovation and the 'industrial commons'

An important element of the manufacturing policy debate in the US focuses on concerns that off-shoring manufacturing operations undermines US industrial leadership in key sectors – in particular, removing a potentially critical element of the capacity to innovate. Influential commentators have pointed to the fact that the off-shoring of production operations is all too often followed by a deterioration in other parts of the industrial system (such as: reduced operations by local suppliers of materials, components, and production technologies; a decline in process engineering skills, manufacturing know-how and leadership; a deterioration of prototyping, test-bed and pilot manufacturing infrastructure). This damage to the so-called 'industrial commons' has the potential to reduce critical interactions, between product development, next generation production technologies and process engineering, which can be a vital source of innovation. Furthermore, because emerging technologies often rely on elements of the 'industrial commons' of more mature sectors, this in turn risks reducing US capacity to compete in some of the most important new industries of the future [Pisano, 2009; Tassey, 2010].

2.2.3 Manufacturing and emerging science and technology

The accelerating pace of scientific discovery and technological innovation, and the opportunities to transform manufacturing [NSTC], are an important focus of the manufacturing research discourse in the US. Although the US leads the world in many areas of scientific discovery through its top research universities and national laboratories – and has a first-rate track record of identifying and conceptualizing innovative opportunities associated with this new science – there is concern that the US is failing to translate these new ideas into US-based high value manufacturing activities [Kota, 2010].

In particular, significant attention is being paid to emerging technologies (such as nanotechnology, and biotechnology) and the realization that their potential to create economic, social and environmental benefits will require new, advanced manufacturing capabilities built on innovations within the manufacturing research base [NSTC, 2008]. Many commentators point to a 'critical frontier of product manufacturing' associated with necessary advances for the development, integration and deployment of novel materials emerging from the science base into new processes, production technologies and products. There is no emerging technology 'silver bullet' that will revitalize US manufacturing by itself; the way forward involves changes to the industrial innovation system itself, including interactions and translation of knowledge between research, innovation and manufacturing.

2.2.4 Interdependence of manufacturing and innovation (and the role of manufacturing research)

The importance of the manufacturing 'industrial commons' to innovation, together with the opportunities presented by novel science and technology, have prompted significant discussion and analysis of the interdependence of manufacturing, applied science and innovation, and the role of manufacturing research. Increasing attention is being paid to the non-sequential nature of the research-to-manufacturing process, and the potential results from an R&D–manufacturing 'ecosystem...where design, product development, and process evolution all benefit from proximity to manufacturing, so that new ideas can be tested and discussed with those working on the ground... locations that possess both strong R&D centers and manufacturing capabilities have a competitive edge' [PCAST, 2004]. There is growing awareness of the interplay between research and manufacturing – the fact that research and manufacturing do not occur in isolation, but in a cyclical dynamic relationship characterized by multiple feedback loops. There is considerable consensus on the need to ensure that manufacturing R&D goes hand-in-hand with scientific discovery to ensure that US manufacturers can quickly transform innovations into processes and products [NSTC, 2008]. This is partly reflected in the focus on industrial–innovation gaps – areas of under-investment in public good R&D investment to address challenges at the interface of manufacturing and innovation (for example early stage technology development, prototype testing, and scale-up and pilot production systems).

2.2.5 'Real engineering' versus 'engineering science'

Concern was expressed by several leading manufacturing research professors that industry problem-solving engineering activities were on the decline in some engineering departments of traditionally industry-facing universities: that engagement in 'real engineering' was declining in favour of 'engineering science'. It was suggested that one consequence of this trend was a decline in the numbers of researchers engaged in tackling research challenges associated with real-world engineering systems. It was argued that this trend towards engineering science was, in particular, driven by pressures associated with building a case for tenured faculty positions. The imperative to publish in the primary academic literature and win research grants from prestigious research foundations meant that researchers were retreating from real-world manufacturing problems. Some of those we interviewed suggested this meant that the proverbial 'Valley of Death' was effectively widening, that is, there were fewer research efforts directly addressing uncertainties associated with the manufacturability of early stage technologies or their integration into existing production processes.

2.2.6 Reshaping the image of 'manufacturing'

Despite the renewed interest at government policy level, many leading manufacturing academics interviewed in the course of this study suggested that interest in academic 'manufacturing' research among students and firms was declining. There was evidence that courses and activities previously labelled as 'manufacturing' were being renamed or associated with broader or more fashionable fields of research, e.g. 'mechanical engineering' or 'global operations'. There was significant agreement that efforts should be made to reshape the image of manufacturing research (and the associated 'vernacular') to more clearly reflect its potential to address some of the most important industrial, social, economic and environmental 'grand challenges'.

2.2.7 Coordination of federal manufacturing research

Several commentators and stakeholders interviewed during the course of this study identified federal agencies' lack of coordination and coherent innovation systems approach to manufacturing R&D as weaknesses. It is notable, however, that the America COMPETES Reauthorization Act of 2010 specifically identified the importance of the coordination of advanced manufacturing research and development [COMPETES, 2010]. The Act requires 'the establishment or designation of a Committee on Technology under National Science and Technology Council' responsible for establishing goals for and coordinating federal programs and activities in advanced manufacturing R&D. The Committee's remit includes facilitating the implementation and commercialization of advances in manufacturing developed through university research and it is charged with presenting a strategic plan to Congress, to be updated every five years. The 2011 NIST workshop referred to in section 2.2, which brought together a range of federal agencies to explore coordinated manufacturing research initiatives, is further reflection of perceived potential opportunities related to manufacturing challenges that might be more effectively addressed by a 'joined-up' approach.

2.2.8 Sustainable manufacturing and manufacturability of green technologies

Sustainable manufacturing and the manufacturability challenges of emerging

US definitions of manufacturing research

In order to navigate the policy literature on manufacturing research, it is important to note that the term 'manufacturing research' has some important variations in emphasis and scope.

Much of the manufacturing research policy debate in the US is focused on so-called 'Advanced Manufacturing'. There are, however, significant variations in stakeholder definitions. The white papers prepared by the Science and Technology Policy Institute for PCAST contain a helpful discussion of these variations and largely reflect the different perspectives held by those stakeholders which we interviewed during the course of this study. The STPI analysis identifies the following variations in emphasis:

- the use of high precision technologies and ICT integrated with a highly skilled, high-performing manufacturing workforce;
- new and emerging industries (i.e. distinguished from traditional manufacturing, such as automotive and steel industry, which are typically low-cost high-volume sectors);
- the translation of novel science and technology into manufacturing processes, technologies and products.

A comprehensive description of the nature of manufacturing R&D was offered in 'Manufacturing the Future: Federal Priorities for Manufacturing R&D', a 2008 report of the Interagency Working Group on Manufacturing R&D of the US National Science and Technology Council [NSTC, 2009]. In particular, the NSTC report usefully distinguishes between manufacturing R&D at different system levels, showing how manufacturing R&D can address any or all of the following:

- unit process-level technologies that improve manufacturing processes, such as machining, deposition, layering, moulding, or joining;
- novel process-level technologies, such as those required to manufacture heterogeneous 3D nanotechnology products;
- machine-level technologies and systems that improve manufacturing productivity, quality, flexibility, or safety for such tasks as fabrication, assembly, or inspection;
- systems-level technologies for innovation in the manufacturing enterprise (e.g. controls, sensors, RFID, and ICT), technologies that support logistics and transportation pathways and infrastructure, and methods and approaches that improve design and decision-making and integrated and collaborative product and process development;
- new knowledge that advances workforce abilities, sustainability, or manufacturing competitiveness; anticipates and responds to global labour, health and safety, and environmental objectives; anticipates and responds to global and domestic availability of energy and materials; and informs supporting investments in energy, communication, information infrastructures.

green technologies feature prominently in almost every discussion of the future of manufacturing research (see also Appendix 2). There have also been a number of high profile workshops and summits addressing the challenges of sustainable manufacturing [NIST, 2011; MIT, 2010b; NIST, 2009].

The Science and Technology Policy Institute 'white papers' produced for the President's Council of Advisors on Science and Technology study on advanced manufacturing suggest that one of the key drivers behind the emergence of a 'new era of manufacturing' will come from focused technological developments that enable sustainable manufacturing. The STPI white papers also highlight, for example, issues such as the 'need for accessible and affordable measurement systems and analytical tools for assessing and managing sustainability across the production process' in the context of developing key technologies to support advanced manufacturing.

A summary of NSF investments related to sustainable manufacturing was presented at MIT's 2010 'Manufacturing Summit', which focused on the theme of sustainable manufacturing [MIT, 2010]. For example, the NSF's Engineering and Education for Sustainability (SEES) initiative highlights the importance of manufacturing to the sustainability agenda: '…research needs and opportunities for advancing sustainability would need to include a vast range of sector-specific and cross-sectoral problem-solving work in fields ranging from green technologies in energy and manufacturing [our emphasis] to urban design to agriculture and natural resources.' References to the SEES portfolio in the NSF's budget to Congress included support for research and education related to 'energy manufacturing, including the scale-up of manufacturing technologies that enable the economic conversion of sunlight, air, and water, using a biological intermediary such as algae, into hydrocarbons.' Sustainable nanomanufacturing is one of the three thrust areas of the National Nanotechnology Initiative – a multi-agency initiative involving most of the US Federal R&D funding organizations.

2.3 Manufacturing research priorities: Future challenges and key topics

The multiplicity of R&D funding agencies in the US, including major mission agencies (such as DOD, DOE and NIST) all with their very particular R&D agendas, makes it more difficult than in some other countries to identify clear national US R&D priorities (and emerging research themes) related to manufacturing research. Nevertheless, a number of key challenges and research priorities feature strongly in the discourse, or were highlighted in our conversations with key manufacturing policy and research leaders, including:

- **Next generation materials** There is a particular emphasis in the US on the opportunities associated with those next generation materials with novel functionalities – both the opportunity to enhance new manufacturing technologies and processes and the opportunities to manufacture entirely new materials-based technologies and products. Significant attention is being paid to challenges associated with process scale-up integration and design for advanced materials, as well as to leveraging simulation technologies and expertise to enhance predictive modelling for advanced materials and materials processing.
- **Sustainable manufacturing and manufacturing of green technologies** As discussed above, sustainable manufacturing features prominently in discussions of future manufacturing research priorities, challenges and opportunities. This theme extends from using novel biotechnologies to manufacture 'green' chemicals [EOP, 2009] to the need for measurement systems and analytical tools for assessing and managing sustainability across the production process system.
- **Leveraging simulation and modelling capabilities to address manufacturing challenges** There is significant focus on the potential opportunities for the US to leverage its strengths in simulation-based engineering and science (as well as ongoing advances in high-performance computational power and tools) for design, materials processes, and manufacturing-systems modelling.

- **Nanomanufacturing** Significant efforts are being directed to addressing nanomanufacturing challenges and the application of nanotechnology to the production technologies and processes of traditional manufacturing industries [EOP, 2009]. NSF's proposed investments in the 'National Nanotechnology Initiative' specifically prioritise nanomanufacturing, including fundamental research funded under the SEBML (Science and Engineering Beyond Moore's Law) initiative.
- **Biotech-related manufacturing challenges and biomanufacturing** Biomanufacturing-related challenges and opportunities have been identified by a number of agencies including NIST (see section on NIST below). There is also significant interest in the manufacturing challenges associated with emerging biotechnologies, such as tissue engineering (regenerative medicine technologies) and synthetic biology. Again, issues associated with scale-up and integration, and the potential to leverage simulation and modelling for design are receiving particular attention.
- **Advanced robotics and cyberphysical manufacturing systems** A research theme that appears within a number of key policy documents is the development of advanced robotics technologies. This priority is driven by an urgency associated with retaining high value manufacturing activities in the US, as well as the aim of responding rapidly to new products and changes in consumer demand [EOP, 2009]. Several experts spoke about cyber-physical systems – future intelligent manufacturing systems with greater adaptability, autonomy, efficiency, functionality, reliability, safety and usability.
- **Manufacturing enterprise systems and responsive, distributed design and production systems** Another set of manufacturing research challenges that features significantly in the discourse on future manufacturing research related to distributed, rapidly responsive, complex product realization. Associated with this theme are priorities associated with the development and integration of the underlying mathematical tools and analytical capabilities for use by enterprises operating highly responsive, distributed production systems. Related themes included the nature of the future manufacturing enterprise itself, including the potential importance of new concepts of manufacturing such as 'open innovation manufacturing' and 'cloud producing'.

2.4 The 'industrial-innovation ecosystem': Manufacturing research funders

The US has a range of different R&D agencies which support manufacturing-related research. Key funders of manufacturing research include not only the National Science Foundation, but also the Department of Defense (DOD), the National Institute for Standards and Technology (NIST) and the Department of Energy (DOE), which runs the US National Laboratories. The manufacturing research organizations, activities, programmes, and initiatives of these agencies are outlined in this section and discussed in more detail in Appendix 3.

2.4.1 National Science Foundation

The US National Science Foundation (NSF) is the federal agency whose activities are most analogous to the UK Research Councils. In particular, the manufacturing research activities of the NSF's Directorate for Engineering (ENG) are the closest in organization and agenda to those of the EPSRC. A significant fraction of the NSF's manufacturing porfolio (and the majority of its manufacturing-related individual investigator awards) comes under the Division of Civil, Mechanical and Manufacturing Innovation (CMMI) – one of the four ENG research divisions. There are also, however, substantial investments in manufacturing-related research made by other divisions, notably the Engineering and Education Centres and the Industrial Innovation Partnerships divisions.

In addition to support for traditional engineering disciplines such as mechanical, industrial, manufacturing and materials engineering, CMMI also invests in multidisciplinary research pursuing 'transformative' advances in real-world industrial systems and technologies, as well as technology platforms with the potential to impact a range of manufacturing-based industrial systems and sectors. CMMI's activities are organized into 'clusters'. In addition to the 'advanced manufacturing' cluster, there are manufacturing-related investments associated with 'systems engineering and design' and 'mechanics and engineering materials'. As well as activities associated with production of physical machines, equipment, etc, there are also investments addressing manufacturing challenges associated with emerging technologies (e.g. nanomanufacturing). CMMI also invests in 'softer' research associated with the non-physical production stages of manufacturing and manufacturing-related decision-systems engineering, such as: manufacturing enterprise systems; engineering design and innovation; operations research; and service enterprise systems.

2.4.2 Department of Defense

One of the most distinctive features of the manufacturing research ecosystem in the United States is the role of the Department of Defense (DOD). The critical role of the DOD in funding manufacturing research in the US was emphasized by the majority of stakeholders consulted as part of this study. Some of the most important DOD activities related to manufacturing R&D are carried out by DARPA (the Defense Advanced Research Projects Agency) and ManTech (the Manufacturing Technology Program).

DARPA invests significant sums in university-based research addressing production research challenges associated with military technologies and systems. Advances made in the production technologies and processes for these mission-critical defence systems often help overcome manufacturability challenges that would be considered too risky by private corporations and too advanced (in terms of technological readiness and demonstration) to attract support from civilian science foundations. DARPA's investments often take emerging processes and technologies to advanced levels of system readiness and deployability. R&D funding from agencies like DARPA allow university researchers to engage in real-world manufacturing problem-solving.

In 2010, DARPA declared its ambition to invest $1B over five years to radically change US manufacturing by attempting to translate the successful model of the US semiconductor manufacturing industry. In particular, DARPA will explore the potential to transfer a manufacturing model where product design companies outsource the production to 'foundries'. The stated goal is to demonstrate the effectiveness of reconfiguring the vertically integrated manufacturing model that is still dominant among many US manufacturers into more efficient manufacturing systems where the 'foundries' distribute their costs across large numbers of different products, while the design-based companies use faster and more flexible facilities for their fabrication needs (e.g. prototypes, pilot manufacturing). In doing so, DARPA hopes to address a fundamental technical challenge associated with the translational process of manufacturing new things.

2.4.3 National Institute for Standards and Technology

The National Institute for Standards and Technology (NIST) has a range of activities supporting manufacturing innovation, including its Manufacturing Extension Partnership (somewhat analogous to the UK Manufacturing Advisory Service), its Manufacturing Engineering Laboratory, and its Technology Innovation Program (which has made a significant number of manufacturing-related investments in recent years). Furthermore, NIST has convened a number of national workshops on important manufacturing-related topics.

NIST's 'Manufacturing Portal' website usefully summarizes its activities across a range of manufacturing-related subject areas: Green Manufacturing; Lean Manufacturing; Metrology; Nanomanufacturing; Ontologies; Process Improvement; Product Data; Robotics; Simulation; Supply Chain; Sustainable Manufacturing; and Systems Integration.

The Technology Innovation Program funds firms and institutions of higher education (and other organizations, e.g. national labs) to address high-risk, high-reward research challenges with the potential to accelerate innovation in areas of critical national need for the United States. Over the last couple of years this process has identified as a priority those challenges associated with the needs of US manufacturers to efficiently move novel materials emerging out of the research base into production and the market place. In particular, the TIP consultation process indicated that competitiveness of process-based industries in the US could be significantly improved through technological innovations to critical manufacturing processes which would 'reduce costs, save time, increase quality or reduce waste' [NIST, 2010b]. The 2010 TIP competition focused on 'Manufacturing and Biomanufacturing: Materials Advances and Critical Processes', while the 2009 TIP competition included the manufacturing theme 'Accelerating the Incorporation of Materials Advances into Manufacturing Processes'.

2.4.4 Department of Energy

Historically, the US Department of Energy (DOE) has made significant research contributions to the development of a range of materials and electronics manufacturing innovations. A notable example is the research carried out by the National Laboratories at Sandia and Lawrence Livermore which led to the development of Extreme Ultraviolet Lithography for nanoscale integrated circuit production.

DOE National Labs continue to carry out some research activities associated with manufacturing challenges related to US energy needs. In fact, one of the questions being explored by the President's Council of Advisors on Science and Technology study of US advanced manufacturing is whether the mission of the national laboratories should be expanded to include 'R&D challenges relevant to a broad range of manufacturing industries'.

The DOE's Office of Energy Efficiency and Renewable Energy has a number of programmes that include investments in manufacturing-related research. One, the Industrial Technologies Program, as well as providing technical assistance to manufacturing firms and sharing of energy-reduction best practices, also invests in targeted R&D programmes associated with next generation manufacturing technologies and processes which are more resource efficient. ITP supports both R&D (including applied research, prototyping, demonstration activities) and also the commercialization of novel energy-efficient technologies. Manufacturing-related cross-cutting technology development areas include 'industrial materials for the future', 'nanomanufacturing', and 'sensors and automation'. Another manufacturing-related ITP programme area targets 'Energy-Intensive Industries'. This programme involves investment in R&D partnerships addressing traditional manufacturing industries, including metal casting, steel, and chemicals.

2.5 The 'industrial-innovation ecosystem': Manufacturing research institutions

In this section, we give a brief overview of different types of manufacturing research-performing institutions in the United States.

2.5.1 Manufacturing research universities

The United States is home to some of the leading manufacturing research universities in the world. Manufacturing leaders and policy makers in other countries consistently identified engineering departments and research centres at universities like Georgia Tech, MIT, Michigan, and Illinois as world-leading institutions in terms of manufacturing research.

These universities have extremely strong levels of industry engagement, including industry-sponsored manufacturing research. Furthermore, many manufacturing firms in the US have a long-established culture of engaging with university research departments and centres.

Manufacturing research is carried out across a variety of departments and schools, not just mechanical or manufacturing engineering (which typically house the more 'physical' production technology and processes research activities), but also departments of industrial and systems engineering (or similar), where manufacturing and manufacturing-based industrial innovation challenges tend to be an important theme.

In the US, university-based industry-collaborating research centres (of different configurations) play a more significant role in connecting to industry than in some other leading manufacturing nations, such as Germany or Japan. Some formal centre models of this type are discussed in more detail below.

2.5.2 Intermediate research institutes

Part of the reason for the important extended role played by public–private university centre models, is that the US has relatively few intermediate research and technology organizations analogous to European RTOs (such as Fraunhofer Institutes, IMEC and LETI) and few applied research national laboratories (such as AIST in Japan) broader than those of specialized agencies.

There are, however, some important intermediate RTOs with significant manufacturing research-related activities, albeit typically still closely connected to leading universities, such as the Georgia Tech Research Institute or the various Fraunhofer USA centres. The Fraunhofer Center for Manufacturing Innovation based on the Boston University campus, for example, provides engineering and R&D services to local and international companies, focusing on product development assistance and advanced manufacturing solutions.

2.5.3 National laboratories

The US National Laboratories of the Department of Energy do engage in energy-related manufacturing research and have significant resources and facilities. Interestingly, one of the questions posed by the ongoing PCAST analysis of advanced manufacturing relates to the potential to extend the role of the national labs to include manufacturing-relevant R&D challenges. The manufacturing-related activities of the Department of Energy are discussed in more detail in Appendix 3

2.5.4 University-industry research centres

As discussed above, university-industry centre models are an important feature of the US innovation system. In particular, they provide an important role in addressing multidisciplinary manufacturing challenges; breaking down 'silos' between traditionally distinct research communities; and translating new knowledge from the science and engineering base into operationalised enabling technologies and systems which can be more readily taken up by industry. Two of the most important (NSF) centre models are discussed in detail below. Appendix 3 contains more general information about the NSF's manufacturing activities.

2.5.5 NSF university-industry research centres

NSF's Engineering Research Centers (ERCs) address multidisciplinary engineering system challenges that have the 'potential to spawn whole new industries or to radically transform the product lines, processing technologies, or service delivery methodologies of current industries'. ERCs provide an environment in which faculty and students can work in close cooperation with their industrial partners to address engineering system challenges that are of significant scale and/or complexity. Although the NSF does not have a manufacturing-specific research centre programme (cf the EPSRC Centres for Innovative Manufacturing) many Engineering Research Centers address manufacturing-related research challenges.

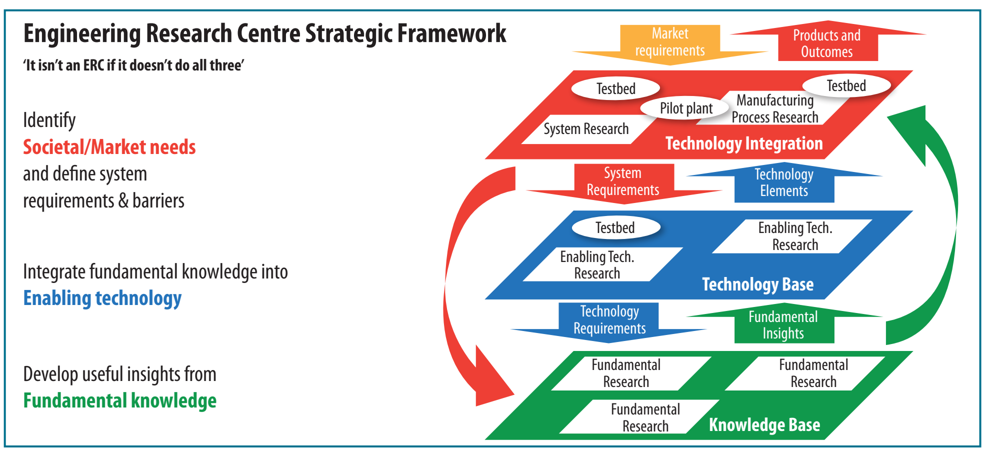

Figure 2.1: The '3-Plane' Strategy Framework for Engineering Research Centers

The ERC programme places particular importance on the translational nature of a centre's research agenda. ERCs are required to have a strategic plan, based on the ERC '3-Plane Chart' illustrated in Figure 1), which identifies critical paths from discovery activities developing new insights from fundamental knowledge through to the innovation of transformative engineering systems. ERC research plans are carefully scrutinized to ensure they have a strategy to address any barriers between the fundamental knowledge, enabling technology, and systems-level research activities.

The value of this system-level framework was commented on by several stakeholders, some suggesting that managing complex multi-participant endeavours is 'not necessarily within the comfort zone of all senior academics'. However, it was also suggested that manufacturing engineers were often very good at this.

In addition to their research, education and knowledge transfer missions, ERCs are also considered testbeds for pioneering effective practices in university-industry engagement and collaborative R&D. ERCs explore new ways of translating research results into new products and services, tackling many of the traditional barriers between different stages of invention and innovation that have hindered cooperation between basic scientists, applied scientists and technologists, and integration engineers, and between universities and industry.

Manufacturing Engineering Research Centers

There have been manufacturing and industrial systems-focused ERCs from the beginning of the program in 1985. Some early ERCs like the Institute for Systems Research (University of Maryland) and the ERC for Net-Shaped Materials (Ohio State University) still exist several years after the end of (10-year) NSF funding. . Recently 'graduated' ERCs include: Reconfigurable Manufacturing Systems (University of Michigan); Packaging Research Center (Georgia Tech); ERC for Environmentally Benign Semiconductor Manufacturing; Center for Innovation in Product Development; Biotechnology Process Engineering Center.

Current manufacturing-related ERCs include: the Center for Advanced Engineering Fibers and Films (Clemson); Center for the Engineering of Living Tissues (GA Tech); Synthetic Biology Engineering Research Center (Berkeley). The latest set of Engineering Research Centers was launched in late 2008 with an increased emphasis on innovation and entrepreneurship, partnerships with small research firms and international collaboration and exchange. Many of the ERCs which are not explicitly focused on manufacturing address important industrial innovation challenges facing existing and emerging manufacturing sectors (e.g. smart lighting, bio-renewable chemicals, medical devices).

Formal evaluations of the ERC programme, as well as inputs received during this study, suggest strong support by manufacturers for NSF investment in critical mass centres which tackle longer term science and engineering advancements and technology platforms, thus underpinning the ever more complex (and expensive) development of new industrial systems and products [Parker, 1997; Roessner, 2004].

NSF's Industry/University Cooperative Research Centers (I/UCRCs) address large industrially-relevant problems, where the multidisciplinary research agenda and (often multi-sector) projects have been developed in close cooperation with industry partners.

The collective nature of financial support by partner firms ensures a focus on research that is of interest to multiple companies (or even a whole industry). I/UCRC research projects are funded primarily by industry members (typically in a ratio of approximately 3:1 industry to NSF investment). Industry is significantly involved in the management of the centre, in particular through the industrial advisory board (IAB) made up of representatives from partner firms. IAB members are involved in overseeing and evaluating research projects, as well as voting on matters of centre policy and research strategy.

The value proposition of I/UCRC membership for companies includes: industry networking; industry-driven R&D projects; access to intellectual property developed during membership; and access to prepublication material such as technical papers. Access to cutting-edge facilities and researcher know-how is a critical benefit of I/UCRC membership. For some manufacturing-related I/UCRCs, the centre can offer value to its industry partners by validating high-impact emerging technologies as well as by cultivating inter-firm alliances through interaction on collaborative testbeds – sometimes the production line of a partner company. Access to students (potential future employees) is another potential attraction for companies. I/UCRCs rely heavily on the involvement of graduate students in research projects. In this way, I/UCRC graduates have developed knowledge, experience and judgement regarding industrially-relevant research.

A number of those interviewed during the course of this study pointed out that, for manufacturing-related centres in particular, interactions with industry partner companies often extend beyond member companies' R&D function. An I/UCRC industrial advisory board member, for example, may be a manager from a manufacturing or engineering department. Given the potential impact of manufacturing research across the entire value chain, centres often cultivate multiple points of contact with different parts of partner firms to enhance the relevance of the research agenda as well as to ensure effective dissemination of information about the centre's activities and findings.

Manufacturing I/UCRCs

There are I/UCRCs addressing a broad range of industry issues and manufacturing-related domains. Advanced Manufacturing is one theme among a number of research challenges associated with industrial innovation in manufacturing sectors, including Advanced Materials, Fabrication and Processing Technology, System Design and Simulation. Recent examples of manufacturing-related IUCRCs include: Center for Engineering Logistics and Distribution; Center for Advanced Cutting Tool Technology; Center for e-Design; Center for Intelligent Maintenance Systems.

2.6 Manufacturing systems research

In our discussion with US manufacturing leaders, research funders and policy-makers, the importance of 'systems perspectives' or 'whole systems approaches' to manufacturing-related research emerged as an important theme. Several influential manufacturing research leaders in the United States pointed to an emerging 'engineering systems' (carefully distinguishing this from 'systems engineering') multidisciplinary field of research and education which brings together aspects of engineering approaches to technology, management and even policy research and the social sciences [CESUN, 2011] to address themes such as engineering management, innovation, and entrepreneurship as well as challenges associated with manufacturing, product development, and industrial engineering.

Several manufacturing research leaders pointed to an increasing demand for engineers with this systems-perspective training and experience (not least system-thinking manufacturing engineers), both within industry and the defence sector. Furthermore, there seemed to be compelling anecdotal evidence that many industrial and engineering systems departments and centres are attracting increasing levels of attention and financial support from industry, as leading manufacturing firms face technological and value chain challenges of accelerating systems complexity.

Systems thinking was also emphasized in the context of graduate student research experience and skills development. A recent US National Academies publication 'The Engineer of 2020' highlights the importance of a 'systems perspective' for the professional context and skills required by engineers in the future. In particular, this document emphasizes that many of the most important current technological and industrial challenges (from the development of next generation biomedical devices to complex manufacturing designs to large systems of networked devices) increasingly require a systems perspective – an approach that looks to achieve synergy and harmony among diverse components of a larger theme.

As discussed above, the NSF's Engineering Research Centers (ERC) focus on next-generation advances in complex engineered systems. Indeed, there is an explicit requirement from the NSF that ERCs provide 'a systems perspective for long-term engineering research and education enabling fresh technologies, productive engineering processes, and innovative products and services.' This ERC systems focus extends to required activities to integrate research with graduate (and undergraduate) education where the curriculum is derived from the systems focus of the centres' research goals.

A number of those interviewed in the course of this study highlighted the importance of manufacturing research funding agencies avoiding the configuration of research programmes and initiatives in 'silos' based around traditional engineering disciplines, which can often inhibit engineers configuring their research agenda to tackle industry systems-level problems and/or stops them bringing in critical expertise from other disciplines to address important research challenges. 'Sustainable manufacturing' was cited on a number of occasions (by a range of stakeholders) as an example of an important emerging research domain where a whole-systems (multidisciplinary) approach was going to be critical to address many key challenges.

2.7 Manufacturing leadership

In the US, the proportion of manufacturing research professors with significant industry careers is smaller than in, say, Germany, but it is striking how many successful manufacturing-related centres have directors with industry experience. Research leaders with significant and broad manufacturing industry experience can also be found embedded in US universities in roles such as 'Professor of Practice' [GATech, 2006] or industrial engagement directors of research centres [NSF, 2009]. Senior ex-industry professionals are also in leadership roles of intermediate research institutes engaged in more industry-focused problem-solving research, e.g. Fraunhofer Institutes, GTRI. Such researchers often have senior positions in local universities as well.

We also observed that the founding Directors of many intermediate manufacturing research institutes or production-related centres of national laboratories had impressive industrial research, manufacturing and management track records in major global corporations. Many successful manufacturing-related ERCs and I/UCRCs have ex-industry senior managers in various roles within the leadership team, often as founding directors. These individuals often have broad industrial career experience within a range of R&D, production and strategic management roles. Many manufacturing centres emphasize the contribution of such individuals and what they bring to the research endeavour: insights into industrial practice and culture; a network of real-world contacts; as well as operational and management experience that can be invaluable in complex, multi-project, multi-partner R&D. Of particular value appears to be the high level of trust such individuals engender in engagements with industry partners, often facilitating more substantial, strategic and long-term collaborations.

Several manufacturing research leaders we spoke to in the US, however, pointed out that many of those who made the transition from major corporations to academia had come from corporations with major research laboratories. Indeed, historical similarities between these labs and university environments – and the freedom of corporate researchers to engage in more fundamental research and publish in the primary literature – was a significant enabling factor in the transition to academia. It was pointed out, however, that with the decline of the great corporate research labs, there were fewer and fewer individuals with this kind of university-compatible industry experience to hire.

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3. Germany

3.1 Introduction

Germany is one of the leading manufacturing and manufacturing research nations. German manufacturing companies generate over a quarter of EU manufacturing turnover, and manufacturing industry makes up approximately a fifth of Germany's value added. Furthermore, an increasing focus of Germany's manufacturing policy is on attracting international manufacturing firms to locate high value production operations in Germany. The quality of (and ease of interaction with) the German manufacturing research base is an important attraction in this regard.

Recognition for manufacturing and for manufacturing-related research underpinning it is a well- established, visible and important feature of German economic and innovation strategies. The strengths of the German production research system were highlighted by many non-German manufacturing research experts interviewed during the course of this study. Significant differences in organisational structures and institutional practices between the German and 'Anglo-Saxon' (US and UK) manufacturing research communities were also highlighted, some of which were considered to play a significant role in enhancing the competitiveness of German manufacturing research (and manufacturing enterprises).

In this chapter we highlight some important aspects of the German approach to manufacturing research, its manufacturing research system, and other features, including:

- Manufacturing R&D policy discourse Recognition for manufacturing and manufacturing-related research underpinning it are well established, visible and important parts of German economic and innovation strategies. By contrast with their counterparts in some other leading economies, German manufacturing stakeholders did not highlight any 'rediscovery' of manufacturing by national policy makers. Production technologies (and related manufacturing research) are an important and established focus area within the German 'High Tech Strategy' and other research-related strategies. [BMBF, 2006].
- Manufacturing research challenges and priorities These include: energy, environmental and sustainability manufacturing challenges; market orientation and strategic product planning; digital manufacturing and advanced automation; production systems and processes for emerging technologies (and non-traditional 'manufacturing' sectors); people in flexible and responsive manufacturing firms (including the demographically-balanced factory, adaptation of working methods for older demographics); flexible production networks and systems for customized manufacturing; protection of production know-how and products in global manufacturing systems.

- Manufacturing research leadership Very many (perhaps most) professors of ‘production technology’ have had significant industrial career experience. Indeed, for several German universities, this is the most common career path route for senior engineering research academics.
- Manufacturing leaders of the future Great importance is also placed on giving production engineering doctoral candidates significant and varied industry problem-solving experiences. Consequently, Germany produces very large numbers of manufacturing-related postgraduate engineers with a doctoral experience somewhat analogous to (a longer and typically more varied version of) the UK EngD.
- Manufacturing research institutions Germany has a diverse collection of research-performing organizations addressing manufacturing-related R&D challenges, including: universities, technical universities, universities of applied sciences, intermediate research and technology organizations (e.g. Fraunhofer Institutes), corporate R&D laboratories and research institutes of the Industrial Research Associations (AiF), as well as Federal and State (Länder)-level institutions.
- Manufacturing research funders There is a variety of Federal funding sources for manufacturing-related R&D. The Federal Ministry of Research and Education (BMBF) is an important investor in manufacturing research, either through the German Research Foundation (DFG), perhaps the closest analogue to the EPSRC, or through core funding provided to independent research institutes (most notably production-related Fraunhofer Institutes), or directly through its Division for Production Systems and Technology. The Federal Ministry for Business and Technology (BMWi) also funds manufacturing-related research (e.g. through programmes run by the German Federation of Industrial Research Associations, AiF).
- Manufacturing research foresight and strategies Germany has developed highly systematic approaches to identifying future manufacturing innovation needs, emerging S&T developments, and associated research funding priorities. One example is a recent analysis of ‘Production Research 2020’ to inform the selection of Federal manufacturing research funding priorities. These exercises often involve extensive stakeholder consultation, competitor analysis and scenario planning exercises. Such exercises are also believed to enhance industry-academic awareness and stimulate healthy debate.
- Production technology strengths International manufacturing research stakeholders highlighted particular strengths of the German manufacturing research system associated with production technologies and engagement in industry-responsive problem-solving.

3.2 Manufacturing and manufacturing research: Policy discourse and debate

In this section, we attempt to reflect the broader context, themes and challenges that dominate the current manufacturing policy debate in Germany, as well as the topics and priorities highlighted within the discourse of the manufacturing research community itself, including:

- a policy focus on maintaining manufacturing leadership in a global economy

- the role of production technologies in underpinning solutions to societal challenges and tomorrow's markets
- the role of production as a pathway for translation of emerging technologies into industries of tomorrow
- the importance of the manufacturing research base to German SMEs ('Mittelstand')
- exercises to map the future challenges (and opportunities) facing German industry and to identify important future science and engineering research fields

3.2.1 Policy focus: maintaining manufacturing leadership in a global economy

Significant attention is being paid to challenges associated with maintaining Germany's leadership as a high-wage economy in the face of increasing global competition, not least the imperative to identify new ways to organize and add value within the manufacturing process. This is reflected in greater emphasis on research domains associated with automation and robotics, the role of people in adaptable manufacturing enterprises, and the demographics of the manufacturing workforce.

3.2.2 Production technologies: underpinning solutions to societal challenges and tomorrow's markets

Production research and technologies are considered essential to a range of sectors and challenges. Within the German discourse regarding technologies with the potential to address important societal challenges, such as health, mobility and sustainability (and the associated market opportunities), manufacturing-related technologies seem to given comparable status to novel bio-, nano- or information and communications technologies [BMBF, 2009].

3.2.3 Production: the pathway for translation of emerging technologies into industries of tomorrow

There is greater emphasis in the German discourse on the role of production research (and production technologies more generally) in translating and deploying more basic science and engineering research (e.g. related to novel ICT, nanotechnology, advanced materials or microsystems) into industry. Discussion of novel emerging technologies focuses on how they can be integrated into production technologies, processes and manufacturing systems.

3.2.4 Manufacturing research: industrial engineering and production technology research

Manufacturing research portfolios and the terminology associated with manufacturing-related research itself reflect industrial strengths and configuration. In particular, there is great emphasis on physical production processes, equipment, technologies, and factories. Business or economics-related research addressing manufacturing enterprises accounts for a much smaller fraction of the publicly-funded 'production research' portfolio; although breaking down barriers between manufacturing engineering and operations and management disciplines is an important goal of some recent initiatives, such as the 'Production Technologies for High Wage Countries' Cluster of Excellence at Aachen [RWTH, 2010].

3.2.5 The German manufacturing research base and SMEs ('Mittelstand')

Germany's 'mittelstand' manufacturing companies – small and medium-sized enterprises (with a large number of family-owned manufacturing engineering firms) – are considered the 'economic backbone' of German industry. Over two-thirds of German employees work in SMEs, many of whom are global leaders in niche engineering market sectors.

Several experts interviewed during the course of this study highlighted the highly supportive environment for German SMEs to engage in and benefit from manufacturing research, for example:

- There is significant interaction between SMEs and both Fraunhofer Institutes (through contract research, access to equipment and advice, etc) and production research institutes in the German Technical Universities.
- Germany has a well-funded 'Federation of Industrial Research Associations' (AiF) which supports applied R&D to improve the competitiveness of German SMEs (see section on AiF below).
- The BMBF's funding of 'Research for Tomorrow's Production' is strongly focused on providing research results for broad use by German SMEs.
- The BMBF's 'KMU-innovativ' programme aims to reduce the risks for SMEs engaging in cutting-edge research by easing access to R&D funding. 'Production technologies' is one of its research priorities.
- The Steinbeis Foundation network offers an efficient mechanism for SMEs to find technical consulting services (e.g. advice, support and potential translational R&D solutions) from universities and universities of applied science to address specific projects. A significant fraction of the larger enterprises within the Steinbeis network offer support to SMEs related to production technologies and manufacturing engineering projects.

3.3 Future research fields and future manufacturing summits and strategies

Germany features regular, systematic, comprehensive and inclusive analysis of manufacturing trends, challenges, emerging production-related research fields and priorities, for example the analyses underpinning the BMBF's 'Framework Concept for Tomorrow's Production' (1999, 2004). More recently, the BMBF commissioned the study 'Production Research 2020' [Abele, 2010]. Led by Professors Eberhard Abele of TU Darmstadt and Gunther Reinhart of TU Munich, the Production Research 2020 initiative involved PTW, IWB and 14 other research institutes, as well as learned societies, industry associations, unions and other public stakeholder organizations. There was substantive and systematic engagement with the German manufacturing research community and over 300 companies to carry out a comprehensive analysis of 'megatrends' influencing the future of manufacturing, to identify key challenges facing German manufacturing firms, and to prioritise a set of emerging research fields and R&D challenges [Abele, 2011].

The first BMBF initiative to emerge from Production Research 2020 was launched in late 2010 with a call for proposals in the area of 'Developing innovative products efficiently' – being faster with the right products to the right customer, in particular addressing challenges associated with 'intertwining' new product development with the development of the necessary production systems and underpinning technologies.

Manufacturing-related research challenges are also identified within the BMBF's Foresight Process. Most recently, an analysis for the BMBF on 'Future Research Fields' by the Fraunhofer Institutes for Systems and Innovation Research (FhG ISI) and for Industrial Engineering (FhG IAO) highlighted the field of 'ProductionConsumption2.0' – an emerging multidisciplinary research domain focusing on transformative socio-technical innovations extending to sustainable industrial and social patterns of materials use [FhG ISI, 2010].

3.4 Manufacturing research challenge and priority R&D themes

Manufacturing research priorities identified in the Production Research 2020 analysis, as well as ongoing important research themes identified in earlier foresight exercises and in interviews with manufacturing research leaders for this study include:

- **energy, environmental and sustainability manufacturing challenges** including production technologies for future energy systems and low carbon technologies (including the development of international standards), resource efficient manufacturing (including cradle-to-cradle), value chains, production systems and processes for low carbon vehicles;
- **market orientation and strategic product planning** including software and product development, refinement of market and product planning tools, and an emphasis on the sustainability of production methods;
- **digital manufacturing and advanced automation** including IT in the factory of tomorrow, simulation and modelling of products, production processes and manufacturing systems, robotics for services and logistics, human-machine interface;
- **production systems and processes for emerging technologies** (and non-traditional 'manufacturing' sectors) including production processes and production equipment for advanced materials, biotech and nanotechnologies ('nano goes production'), pharmaceutical factories and micro-level processing;
- **people in flexible and responsive manufacturing firms** including the demographically-balanced factory, adaptation of working methods for older demographics;
- **flexible production networks and systems for customized production** including development of innovative products efficiently, integration of material engineering development, production technologies and product development methodologies, flexible manufacturing organization structures and supply chain management;
- **protection of production know-how and products in global manufacturing systems** including research addressing product piracy, production technologies for marking and registration.

3.5 German manufacturing research institutions

Germany has a diverse collection of research-performing organizations, including:

universities, universities of applied sciences ('Fachhochschule'), non-university research institutes (e.g. Helmhotlz, Leibnitz and Max Planck Institutes), intermediate research and technology organizations (e.g. Fraunhofer Institutes), corporate R&D laboratories and research institutes of the Industrial Research Associations (AiF), as well as Federal and State (Länder)-level institutions. Some of the most important manufacturing research organizations are described briefly below.

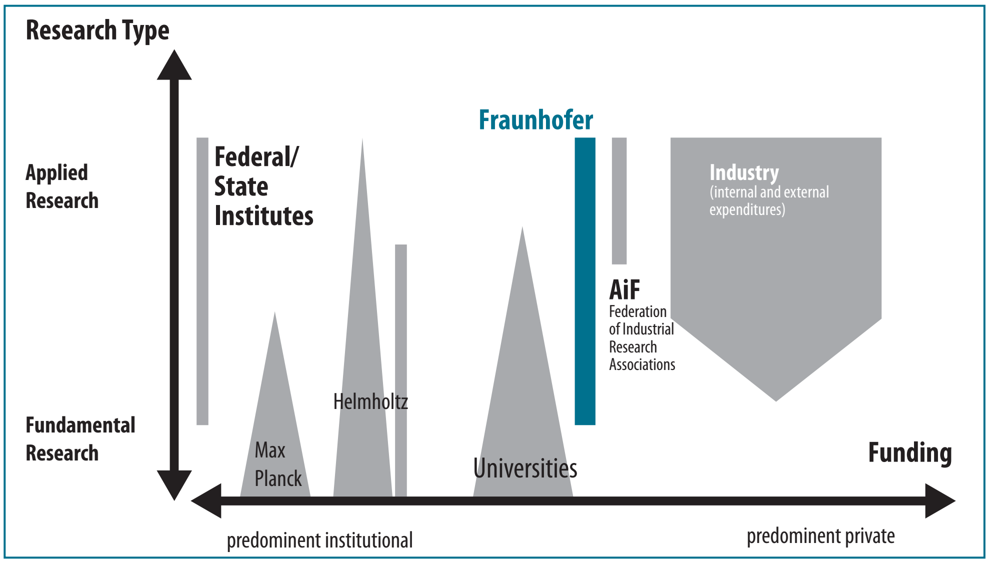

Figure 3.1: Schematic representing some of the main research performing organizations in Germany [Source: BMBF]

3.5.1 Academic manufacturing research

Academic production research (and related engineering research fields) is dominated by the leading Technical Universities. In particular, the TU9 network of leading Institutes of Technology[1] attracts the majority of engineering research investment by the DFG. Nearly 57% of all engineering doctorates in Germany are awarded by the TU9. German technical universities with particularly strong production engineering research portfolios include Hannover U, Dortmund TU and Aachen RWTH, but there is strength in depth in manufacturing-related research across a large number of universities.

Indeed, several international manufacturing research leaders highlighted that – unlike, for example, the United States, where some of the best manufacturing-related research and high level industrial engagement is carried out in a relatively small number of elite engineering universities – there is high quality manufacturing research and industry engagement distributed throughout the German university system. The DFG's Funding Ranking 2009 report [DFG, 2009] contains a useful analysis of their engineering investments across the German higher education system (see Figure 3.2). By comparison with other leading manufacturing research nations, German universities, in particular Technical Universities, engage in a greater degree of real-world problem solving.

[1] RWTH Aachen, TU Berlin, TU Braunschweig, TU Darmstadt, TU Dresden, Leibniz Universität Hannover, Karlsruhe Institute of Technology, TU München, Universität Stuttgart

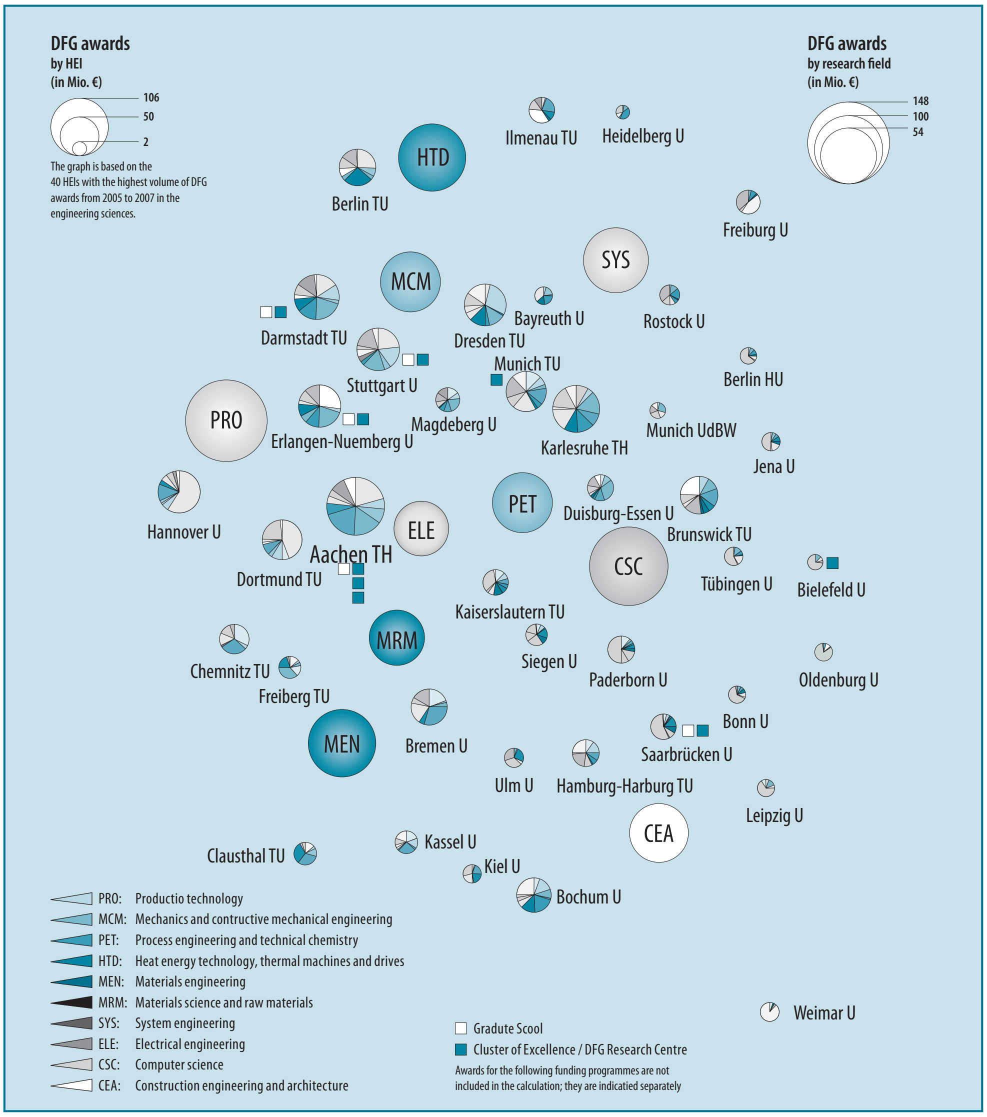

Figure 3.2: Schematic representing the DFG investment in some manufacturing-related engineering domains; and in particular universities [Source: DFG, 2009]

3.5.2 Fraunhofer Institutes and manufacturing research

The Fraunhofer-Gesellschaft is the EU's largest applied research organisation, made up of 59 Fraunhofer Institutes (as well as a number of smaller research units). The Fraunhofer Institutes employ over fifteen thousand staff, mainly qualified science and engineering researchers, but also significant numbers of professional industrial and design engineers. Fraunhofer Institutes carry out R&D at the interface between basic research and industrial application. The Fraunhofer Institutes engage with a broad range of industrial clients in both the manufacturing and service sectors, as well as with Federal and state (Länder) agencies. The Fraunhofer Institutes have an annual R&D budget of approximately €1.5 billion, of which more than €1 billion is generated through contract research. Two-thirds of the R&D revenue is based on contract R&D for industrial clients and public research projects; the final third coming from institutional 'block grant' funding from the Federal government.

A significant number of Fraunhofer Institutes engage in manufacturing-related research. Of particular note are the institutes involved in the Fraunhofer 'Group for Production' – an initiative involving seven Fraunhofer Institutes which brings together their collective range of expertise, facilities and experience to more effectively carry out manufacturing-related R&D. The Group for Production addresses research themes associated with product development, manufacturing technologies, manufacturing systems, production processes, production organization, and logistics. There are also manufacturing-related activities within other Fraunhofer groupings; for example, the Institute for Manufacturing Engineering and Applied Materials Research is affiliated with the 'Materials and Components' Group and the Institute for Process Engineering and Packaging is affiliated with the 'Life Sciences' Group.

Some Fraunhofer Institutes are also affiliated with 'Alliances' which facilitate access for customers to research findings and services related to emerging technology platforms and R&D domains of current interest. Manufacturing-related Alliances include the 'Numerical Simulation of Products', 'Rapid Prototyping', and 'AutoMOBILE Production' alliances.

3.6 Manufacturing research funders

German Federal support for manufacturing-related R&D is primarily funded by the Federal Ministry of Research and Education through: the German Research Foundation (DFG); core funding of independent research institutes, most notably production-related Fraunhofer Institutes; direct funding by the BMBF through its Division for Production Systems and Technology. The Federal Ministry for Business and Technology (BMWi) also funds manufacturing-related research, notably through the German Federation of Industrial Research Associations (AiF).

3.6.1 The Deutsche Forschungsgemeinschaft (DFG)

The DFG is the German Research Foundation, the research funding agency most analogous to the UK EPSRC. The DFG funds most of its manufacturing-related research throughout its Engineering Sciences investment portfolio. The categorization and organization of Engineering Sciences is slightly different from that of the EPSRC. Many of the manufacturing investments are contained within the category 'Mechanical and Industrial Engineering', but other relevant grants are assigned to categories such as 'Thermal Engineering and Process Engineering'; 'Materials Science and Engineering'; and 'Electrical and Systems Engineering'. Mechanical and Industrial Engineering is further divided into the subcategories of 'Mechanics and Constructive Mechanical Engineering' and 'Production Technology'. In many conversations with German experts, 'manufacturing research' was generally interpreted as 'production technology research' and was taken to include: metal-cutting manufacturing engineering; primary shaping and re-shaping technology; micro-, precision, mounting, joining and separation technology; plastics engineering; production automation, as well as factory operation and operations management. The distribution of the DFG's manufacturing engineering research portfolio is nicely analysed in their Funding Ranking reports [DFG, 2009] which was discussed briefly in section 3.5.1.

DFG Centre programmes

One of the DFG's main initiatives investing in collaborative research is the Collaborative Research Centres (CRC) programme. CRCs are institutions established at universities with potential funding for up to 12 years to enable researchers to pursue complex, long-term, multidisciplinary research agendas which require a critical mass of research capabilities that cross the boundaries of disciplines, institutes, departments and faculties [DFG, 2006; DFG, 2008]. Although there is no manufacturing-specific centres programme, a significant number of CRCs address manufacturing-related research challenges, in particular within the category of 'mechanical and industrial engineering'.

The research agendas of the manufacturing-related CRCs are quite basic in nature, aiming to advance fundamental insights into industrial engineering systems. The DFG also invests in the practical real-world industrial applications of CRC research findings through its 'Transfer Projects' mechanism which helps translate research findings to industrial partners. Particular value is placed on ensuring that insights from practice acquired during Transfer Projects are absorbed into the CRC research agenda and university research community. Again, as so often in discussions about German engineering research outputs, particular importance is placed on creating engineers who can bring the skills, insights and experiences developed during the CRC Transfer Projects out into German industry.

Cluster of Excellence 'Integrative Production Technology for High-wage Countries'

One of the flagship manufacturing research centre initiatives of the DFG is the Aachen Cluster of Excellence 'Integrative Production Technology for High-wage Countries' [RWTH, 2010]. The Cluster's theme reflects the high level of importance attached to maintaining production technology leadership within a high-wage economy. The mission of the Aachen centre is to develop promising, sustainable production technologies and insights which can make a substantial contribution to finding solutions for maintaining production which is relevant for the Germany's high-wage labour market [Klocke, 2009].

The centre brings together 19 professors from the Department of Materials and Production Technology, as well as affiliated research institutes, including neighbouring Fraunhofer Institutes. The research focus is on products that address both niche markets and volume markets. Research projects include activities related to virtual-, hybrid- and self-optimising production systems, as well as individualized production processes and strategies. The research agenda also aims to develop fundamental insights underpinning a theory of 'production science', bringing together not only aspects of physical production technologies and processes, but also organisational and management dimensions into a holistic framework to help German firms implement competitive production strategies within a global market.

3.6.2 German Federation of Industrial Research Associations (AiF)

The AiF is a non-profit organization that promotes R&D activities supporting small and medium-sized enterprises (SMEs). The AiF is made up of an industry-based innovations network covering over a hundred non-commercial industry-based research consortia. The Federation has 46 research facilities of its own and cooperates with several hundred closely affiliated institutes [AiF, 2005].

Most of these facilities include activities that help address manufacturing-related R&D challenges. The AiF operates in all industry sectors and across a wide range of manufacturing-related applied research domains, and has an annual budget of approximately €300M. Some of the R&D activities of the AiF take place in their own institutes, or in cooperation with other research organizations (including universities and Fraunhofer Institutes).

AiF promotes R&D for SMEs in two ways:

1. administering governmental R&D support programmes addressing the research needs of SMEs (mainly funded by the Ministry of Education and Research and Ministry of Economics and Technology).
2. organising collective research programmes for the benefit of entire industrial sectors, where themes for research projects are identified 'bottom up' based on common challenges and R&D needs faced by industry association members.

3.7 Practitioner-focused dissemination of manufacturing research findings

The German manufacturing research community seems to place relatively greater value on dissemination via media that will reach the factories and other parts of manufacturing operations. In particular, with this audience in mind, a significant fraction of manufacturing research findings are published in German-language academic journals, as well as disseminated through industry journals and magazines.

Estimates, based on analyses of some of the leading production technology, manufacturing and mechanical engineering institutes in top German universities, suggested that 60–70% of published findings do not appear in (English language) journals that are readily available to international academic and industrial researchers.

Several manufacturing research leaders interviewed during the course of this study suggested that many important German manufacturing engineering research findings may not be readily accessible via the English language academic literature.

One important aspect of the Excellence Initiative (see box below) is the promotion of more 'scientific' academic research of high quality which has international visibility and connectedness. In the context of production research, this is likely to result in greater prioritisation of publication within the primary international (English-language) literature.

3.8 Manufacturing research leaders

German production research professors (in particular those at the Technical Universities) have significant depth and breadth of industrial experience – not only in production research, but often within a broad range of manufacturing, management and strategy roles. In common with many other German engineering professors, most professors of 'production technology' have significant industrial career experience, typically 10–15 years. Indeed, for the Technical Universities, this is the most common career path route for senior manufacturing research academics [Altan, 2996; Altan, 2003; Cummins, 2011].

Several experts interviewed during the course of this study highlighted the very high numbers of CEOs, CTOs and other senior management figures in German manufacturing firms with engineering PhDs. It was suggested that this has important consequences for awareness within firms of the potential of manufacturing research to enhance their competitiveness; as well as a stronger network of contacts and trust between industry and the manufacturing research base.

The Directors of Fraunhofer Institutes are invariably also full professors at local universities. This helps strengthen the relationships, knowledge transfer and mobility of researchers between the manufacturing research base, Fraunhofer Institutes and (ultimately)industry. This also helps some diploma engineers and PhD engineers to carry out their research projects at local Fraunhofer Institutes and/or engage in industry problem-solving research activities [Cummins, 2010].

3.9 Manufacturing leaders of tomorrow: The manufacturing research doctoral experience

There appears to be greater emphasis on highly skilled, research-experienced workforce for the manufacturing sector as an output of manufacturing research investments. The relatively high fraction of German nationals among manufacturing-related engineering doctoral researchers was also highlighted by those interviewed.

Dr. Ing. ('Doktor Ingenieur') candidates are typically paid salaries (rather than receiving studentships) and are considered part of the engineering staff of their institute. Doctoral candidates engage in a range of activities in addition to their doctoral research, for example: coordination of research projects, preparation of grant proposals, engaging in industry problem-solving research, as well as teaching, advising and helping supervise students. Significant emphasis is placed on giving production engineering doctoral candidates significant and varied industry problem-solving experience. The variety and multiplicity of industry-relevant projects is considered an important factor in instilling judgement and experience, which is extremely valuable when they enter the workforce as doctoral graduates [Cummins, 2011].

The Graduate School for advanced Manufacturing Engineering (GSaME)

As part of the Graduate Schools strand of the National 'Excellence Initiative' (funded through the DFG), the University of Stuttgart hosts a flagship 'Graduate School for advanced Manufacturing Engineering', GSaME [GSaME, 2010]. The school is directed by Engelbert Westkämper, Director of the local Fraunhofer Institute for Factory Operation and Automation (IFF). GSaME focuses on producing manufacturing leaders who can plan, design and manage the factories and manufacturing systems of the future. There is a particular focus on collaborative, multidisciplinary activities: connecting theory and practice, technology and management, research and application. GSaME research themes include: sustainable manufacturing; intelligent production systems; digital and virtual manufacturing; knowledge-based management; ICT for manufacturing; value chains and networking in manufacturing; process engineering. Another important theme is the 'Stuttgart Enterprise Model' which applies a systems perspective to understanding manufacturing industrial structures and processes.

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4. Singapore

4.1 Summary

Manufacturing continues to be a hugely important part of the Singapore economy. Stakeholders in Singapore credit the success of manufacturing on a strong technology base and emphasize a ‘strong nexus’ with increasing R&D activity. Some of the main issues, actors and features related to the manufacturing research landscape in Singapore are summarized in this chapter.

Challenges and drivers facing Singapore manufacturing which are shaping the manufacturing research agenda include:

- climate change and sustainability
- emerging industries, in particular biotech- and nanotech-enabled
- productivity of Singapore-based manufacturing relative to competing economies
- competition from China

Priority and emerging manufacturing research themes identified by policy makers and leading manufacturing research (and manufacturing) experts include:

- material science and engineering, e.g. nano-technology and robotics
- green and sustainable manufacturing
- precision engineering for innovation

SIMTech (the Singapore Institute of Manufacturing Technology) is a dominant actor in the Singapore manufacturing research landscape. Key SIMTech characteristics include:

- the extent of its global connectedness (to industry and academia)
- its role in supporting manufacturing industry, both MNCs and SMEs
- emphasis and strengths related to physical production processes and technologies
- increasing coordination with other institutes on manufacturing challenges related to emerging S&T

Joint initiatives between A*STAR (the Singapore Agency for Technology and Research) and universities are an increasingly important part of the manufacturing research ecosystem. There is strong engagement and leveraging between the intermediate RTOs (including SIMTech) and university-based research, e.g. via joint programmes and shared equipment.

Support for SMEs is an increasing focus within manufacturing-related initiatives, including the A*STAR programme GET-UP (Grow Enterprise Through Technology

Upgrading) and other engagements.

The Economic Development Board plays a key role in setting the agenda and is an important funder of manufacturing research in its own right.

4.2 Context: Singapore industrial innovation policies and ecosystem

Important insights into Singapore's industrial innovation priorities can be learned from those aspects of the 'Research, Innovation and Enterprise Plan 2015' relevant to manufacturing. This emphasizes:

- global trends driving changes in manufacturing, including climate change and sustainability, emerging biotech and nanotech industries, and competition from China. Industry needs high value manufacturing, innovations and new technologies to respond
- potential for more multidisciplinary inter-research institute programmes
- new ways of engaging in (manufacturing) research, e.g. open innovation to enhance impact

Broadly speaking, the national R&D funding system is organized along two main strands managed by the Ministry of Trade and Industry and the Ministry of Education. The Ministry of Trade and Industry (MTI) activities focus on mission-oriented research, primarily through initiatives and investments by A*STAR and EDB, whereas the Ministry of Education oversees academic, investigator-led research through the universities and polytechnics.

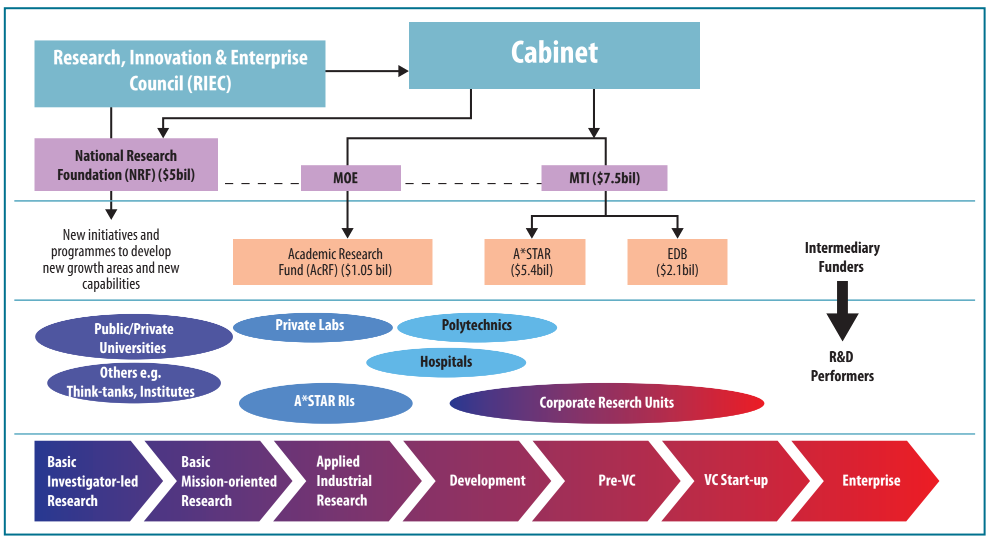

Figure 4.1: Singapore National R&D Framework [MTI, 2006]

Traditionally, Singapore policy makers and the manufacturing research community have used a narrow definition of 'manufacturing research' (referring largely to physical production engineering-related domains), but this is changing as increasing attention is paid to multidisciplinary, multi-sector opportunities, especially in emerging industries. Importantly, however, the larger national research agenda is driven by interest in supporting innovation needs of Singapore's manufacturing industry base.

4.3 Key funding agencies and manufacturing research stakeholders

4.3.1 The Agency for Science, Technology and Research (A*STAR)

A*STAR oversees 14 research institutes and seven consortia and centres, and supports extramural research with the universities and other local and international partners. Eight of the research institutes – including the Singapore Institute for Manufacturing Technology (SIMTech) are overseen by A*STAR's Science and Engineering Research Council. Although SIMTech is the primary manufacturing research institute, some other institutes also address manufacturing-related challenges associated with their technology base and research domains.

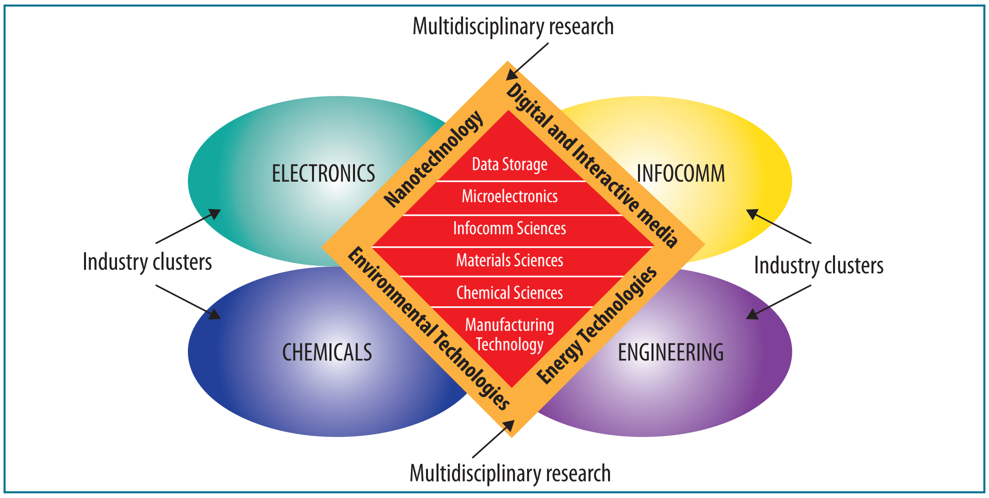

*Figure 4.2: A*STAR R&D Framework for Industry: supporting multidisciplinary research [Source: A*STAR]*

A*STAR invests in manufacturing research two ways:

1. Through research institutes addressing manufacturing research challenges as mentioned above. These are A*STAR institutes, funded directly by and reporting to the agency.
2. Leveraging Singapore's academic institutions to address manufacturing challenges by funding thematic research programmes which can be undertaken by academic staff, teaming up with research teams in the research institutes or even collaborators abroad.

SIMTech and other A*STAR research institutes carry out contract R&D for manufacturing firms – providing solutions to their manufacturing problems, transferring know-how and training their people.

A*STAR has a special programme to help support manufacturing firms (mostly SMEs) called GET-UP (Grow Enterprise Through Technology Upgrading). Its features include: seconding research scientists and engineers to the companies for up to two years; assisting companies in technology management by attaching senior managers from A*STAR; assisting companies to formulate technology strategies all the way to the drafting of technology roadmaps.

A*STAR's research capabilities are an integral component of Singapore's industry development strategy. A*STAR plays an active role in supporting EDB's investment promotion efforts to attract manufacturing and R&D activities to Singapore.

A*STAR also carries out technology scans of major technological, industrial and economic trends. From these analyses, possible scenarios of the future research needs of manufacturing industries are explored. These analyses are used to inform A*STAR research institute strategies and priorities for developing critical R&D competencies. In particular, these scans are used to update intramural programmes, initiatives and infrastructure so as to stay relevant to Singapore's manufacturing base; as well as to inform the broader Singapore research community about the priorities and directions of A*STAR's extramural programmes with universities and other stakeholders.

4.3.2 SIMTech

The Singapore Institute of Manufacturing Technology (SIMTech) 'develops high value manufacturing technology and human capital to enhance the competitiveness of Singapore's manufacturing industry'. It has completed over 900 projects with more than 500 companies, large and small, in manufacturing-based sectors such as electronics, semiconductor, precision engineering, medical technology, aerospace, automotive, marine, and logistics.

SIMTech's mission is to:

- create intellectual capital through the generation, application and commercialisation of advanced manufacturing science and technology
- nurture research scientists and engineers by providing opportunities to do use-inspired research for industry
- contribute to Singapore's industrial capital by collaborating in projects and sharing research expertise and infrastructure with industry

Its research divisions include: manufacturing process (forming-, machining-, joining-, surface technologies, etc); manufacturing automation (mechatronics, precision measurements, etc); and manufacturing systems (manufacturing execution and control, planning and operations management). It also includes special research programmes in microfluidics manufacturing and large area processing.

Industrial innovation centres focus on RFID, sustainable manufacturing, and precision engineering. Its Innovation and Commercialisation Department has focus areas such as: Equipment Innovation and Development; Sustainability and Technology Assessment; Product Innovation and Development. There is a growing emphasis on collaborative work across organisational boundaries, for example the 'MedTech Manufacturing Initiative' [A*STAR, 2010].

SIMTech priorities and approach to manufacturing research are somewhat reflected in its focus areas and initiatives, for example:

- joint labs with university partners
- manufacturing productivity centres
- Precision Engineering Centre of Innovation
- seeding and growing emerging industries

One of the most important new initiatives is SIMTech's 'Sustainable Manufacturing

Centre' (SMC) which aims to develop methodologies and tools for assessment of sustainability in manufacturing, as well as R&D for sustainable manufacturing technologies, products and services. Furthermore, the new centre will provide Singapore's manufacturing industries with consultancy services and transfer of technologies for sustainability. The SMC will also support the development of human capital for sustainable manufacturing through 'Workforce Skills Qualifications', sustainable technology workshops and seminars.

4.3.2.1 SIMTech leadership and industry experience

Reflecting observations elsewhere in this report, Singapore stakeholders emphasized the value and impact of industry-experienced manufacturing leadership at SIMTech. The founding Director of SIMTech[1], Frans Carpay, had previously spent 40 years at the Philips corporation where, among other things he led development, manufacturing and market introduction of the compact disc; was CTO of a number of Philips joint ventures (e.g. with Seagate, DuPont); and was Director of Philips Research before his move to Singapore. The current Director, Lim Ser Yong had a distinguished career at the Fairchild Corporation.

More generally, SIMTech has a significant number of staff with industrial experience. Furthermore, SIMTech facilitates staff with no industry experience to be attached to a manufacturing firm for periods of at least six months.

4.3.3 The Economic Development Board (EDB)

The Singapore Economic Development Board is the lead government agency with responsibility for economic growth, development and inward investment. In addition, the EDB is an important research funder and influential stakeholder in shaping Singapore's manufacturing research agenda. The priorities for public research are developed and aligned with EDB's manufacturing agenda.

As part of the EDB's mission and strategy to attract and develop future manufacturing industries, it funds R&D in manufacturing-related and emerging technology areas. EDB engages in a range of manufacturing research-related activities, from stimulating relevant training programmes to major investments in frontier R&D domains through the establishment of new university research institutes (outside A*STAR), for example the SERIS (Solar Energy Research Institute of Singapore) at the National University of Singapore which trains engineers, creates intellectual property, and carries out joint R&D with local companies.

As part of its activities the EDB identifies areas of engineering, sciences and technologies needed to support targeted capability levels and competitiveness of Singapore-based manufacturing and services clusters. These include identifying focused S&T research areas for each industry cluster, as well as broad-based manufacturing and other technologies that cut across various industry sectors.

4.3.4 The National Research Foundation (NRF)

The National Research Foundation (NRF) is a department under the Prime Minister's Office with a remit to:

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[1] Originally called Gintic

- provide secretariat support to the Research, Innovation and Enterprise Council (RIEC), chaired by the Prime Minister;
- coordinate the research of different agencies within the larger national framework in order to provide a coherent strategic overview and direction;
- develop policies and plans associated with the national R&D agenda;
- implement national research, innovation and enterprise strategies;
- allocate funding to programmes that meet NRF's strategic objectives.

Although the NRF's research funding activities related to manufacturing research are more indirect than those of A*STAR or EDB, it does fund research in emerging areas which have a role in underpinning aspects of new manufacturing industries of the future. Examples include environment and energy (e.g. research related to new water) and interactive and digital media.

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5. Sweden

5.1 Summary

Manufacturing industries are of critical importance to the Swedish economy, generating 50% of Sweden's total export of goods. Swedish industry is made up of large global corporations and many small firms. Almost 350,000 people work in Swedish engineering companies with a further 700,000 employed in companies dependent on the success of engineering firms. Some important features of the Swedish manufacturing research landscape which supports these industries are outlined below.

'Production science' is one of the identified strategic research priority themes of the most recent research and innovation bill of the Ministry of Education and Research.

Globalization and sustainability: the manufacturing research agenda and policies are strongly influenced by drivers of change in the manufacturing base.

Small and medium-sized enterprises play an important role within the structure of Swedish industry. Swedish manufacturing industrial systems are highly distributed, made up of extended value chains of small Swedish companies (typically smaller than the average European SME) working with much larger Swedish manufacturing corporations. Value chain and logistics research in support of this SME base is, consequently, an important priority in Sweden.

Swedish Production 2020: Industry, academia, learned societies and RTOs work together on national strategy for production research.

Challenges facing Swedish manufacturing (identified by industrial and academic groups) include: sustainable production; flexible production; the role of humans in production systems; digital and knowledge-based production; production of innovative products; parallel product realisation.

Collaborative and systems approaches to manufacturing are considered strengths of production research, and feature prominently in policies and programmes.

Priority and emerging manufacturing research themes include:

- **production systems** including topics such as adaptive production systems, virtual factory, role of humans in production systems, production logistics and enterprise networks
- **integrated production and product development** including topics such as production requirements in early stages of product development, methods for virtual production and product development, analysis and optimisation of production and product development
- **manufacturing processes** including topics such as: processing of novel materials and compounds, virtual development methods for material processing and forming,

manufacturing technology for micro- and nano-structures, management of measurement data, and materials characterization (from a process perspective)

5.2 Key funding agencies and production research stakeholders

Academic manufacturing research in Sweden is funded from a variety of public sources, including: VINNOVA (Swedish Government Agency for Innovation Systems), NUTEK (Swedish Agency for Economic and Regional Growth) and the Swedish Research Council (VR) and the Swedish Foundation for Strategic Research (SFF). The principal government ministry with responsibilities for public research funding is the Ministry of Education and Research.

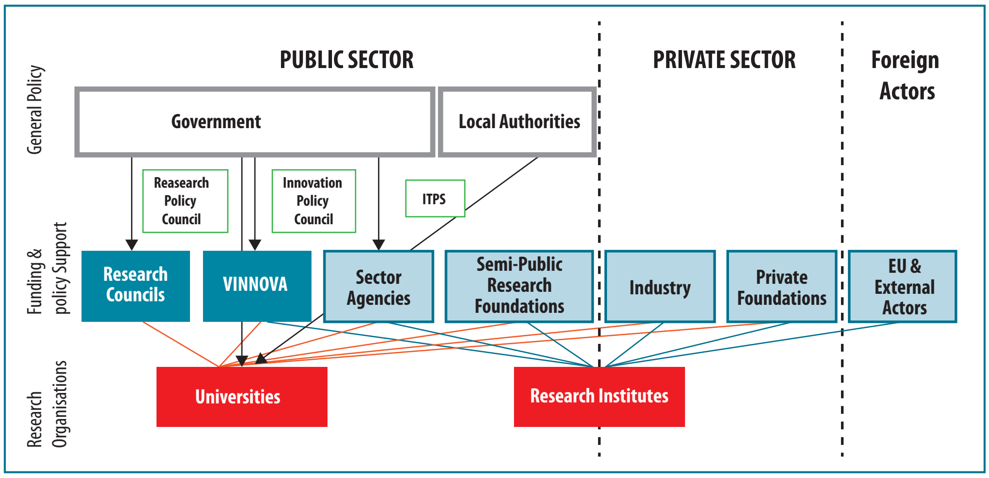

Figure 5.1: Schematic of the Research System of Sweden [ERAWatch(a)]

Other important manufacturing research stakeholders in Sweden include: Teknikföretagen (the Association of Swedish Engineering Industries), the Swedish Production Academy, the Royal Swedish Academy of Engineering Sciences (IVA), and Swerea (the production-related members of the Research Institutes of Sweden).

5.2.1 Ministry of Education and Research

The Swedish Government's 2008 research and innovation bill 'A Boost to Research and Innovation' [ref] allocated additional research investment of SEK 5B over the period 2009–12. In particular, these investments were targeted at areas deemed strategically important to Swedish society and industry, where Swedish research is already world-class, and where society and the business sector have a major need for new knowledge.

One of the strategic priority research areas identified in this bill was 'Production science'. Other manufacturing-related strategic areas included: materials science, transport research, nanotechnology, and sustainable use of resources. In 2009, the relevant R&D and innovation agencies (VINNOVA, Swedish Research Council, etc) assessed which universities and other higher education institutions were best suited to carry out the strategic initiatives. Ultimately two awards were made by VINNOVA under the Production Science area: the 'Sustainable Production Initiative' led by Chalmers and Lund universities; and the 'Initiative for Excellence in Production Research (XPRES)' a joint initiative between the Royal Institute of Technology, Stockholm (KTH), Mälardalens University (MDH) and the Swerea Research Group.

5.2.2 Swedish Foundation for Strategic Research (SFF)

The mission of the Swedish Foundation for Strategic Research is to support scientific, technological and medical research to promote the development of a strong research environment in areas of importance for Sweden's future competitiveness. The SFF invests both in basic research and applied research, as well as research that translates knowledge from fundamental knowledge to application. SFF has a suite of funding mechanisms (strategic research centres, framework grants, individual grants, mobility grants, etc). A significant fraction of SFF investment is made in manufacturing-related research domains, such as 'product realization and process engineering' and 'materials science and engineering', as well as targeting production-related research challenges in electronics, photonics, bioengineering, etc.

An important SFF programme for manufacturing is 'ProViking'. Starting in 2002, SSF invested SEK 180M (~UK£17M) in a five-year research programme in the area of Product Realization. This programme – 'ProViking' – included support for a national research school. This programme was renewed for the period 2008–13 with a 210M SEK (~UK£20M) investment. An important emphasis within the ProViking initiative is the importance of 'holistic perspective and systems thinking' in product realization and manufacturing research.

5.2.3 The Swedish Research Council (Vetenskapsrådet)

The Swedish Research Council (VR) is a government agency that provides funding for basic research. The natural and engineering sciences division funds research in manufacturing-related research in process engineering, materials science, systems engineering and mechanical engineering.

5.2.4 VINNOVA

Established in 2001, VINNOVA is the Swedish Government's 'Agency for Innovation Systems'. VINNOVA's mission is to increase the competitiveness of Swedish public research base and firms through funding needs-driven R&D (~€220M / year). Most VINNOVA grants involve industrial cost-share – typically 50% – which effectively doubles the annual research investment budget. VINNOVA has a variety of research programmes related to manufacturing. Recent programmes include: product realization (Manufacturing in Continuous Change; Production Strategies and Models for Product Realization); working life initiatives; designed materials. In addition VINNOVA invests, on behalf of the Ministry for Education and Research, in the strategic priority area of 'Production Science'.

VINNOVA's 'product realization' programmes encompass all activities related to developing and realizing product solutions addressing customer need – i.e. both product development and production development. VINNOVA's research investments under its 'working life initiatives' focus on processes of innovation and change within (and around) firms, including organisation and operations management, as well as innovation processes and industrial and organisational change. Many of VINNOVA's materials engineering investments are strongly focussed on manufacturing. The 'designed materials' programme has two components: one related to assessing potential for commercially viable material concepts (and commercialization implementation); another focused on translating verified concepts into industrially viable solutions and/or creating value chains which effectively support the development, manufacture and marketing of these novel material concepts.

5.2.5 Teknikföretagen

Teknikföretagen is the Association of Swedish Engineering Industries. Its member companies are active in manufacturing-based sectors such as: industrial machinery, telecoms, computer technologies, photonics, aerospace and automotive.

Teknikföretagen's 'Produktionsforum' works with other stakeholders to address key issues and develop strategies for production research in Sweden, for example making important contributions to the IVA study 'Production for Competitiveness', and playing a lead role in the subsequent 'Swedish Production 2020' (discussed below). Teknikföretagen also supports its members through initiatives such as its 'Produktionslyftet' programme, which aims to enhance production know-how in Sweden's SME base through training and practical advice, in particular in areas such as lean production.

5.2.6 Research Institutes of Sweden

Sweden also has a network of RTOs – the Research Institutes of Sweden (RISE). RISE Institutes with a particular focus on production are the Swerea RTOs: IVF (R&D and training for the manufacturing industry); KIMAB (corrosion and metals R&D); MEFOS (R&D and consulting in pyrometallurgy, heating and metalworking); SICOMP (manufacturing and design of composite materials); and SWECAST (R&D and training for the foundry and casting industry).

5.2.7 The Royal Swedish Academy of Engineering Sciences

The Royal Swedish Academy of Engineering Sciences (IVA) is an independent forum that brings together experts from different disciplines and countries, promoting exchange of knowledge and ideas between industry, academia, policy makers and other stakeholders. IVA has played an important role in supporting the Swedish production research agenda, not least through its recent project on 'Production for Competitiveness' [IVA, 2006].

Swedish Production 2020

In 2007, manufacturing firms, academia, learned societies and research and technology organizations worked together to develop the agenda for a national strategy for production research that would meet the challenges and opportunities facing Sweden's manufacturing industries. The resulting document – 'Swedish Production 2020' – was a collaboration between Teknikföretagen, the Swedish Production Academy, and Swerea IVF. Swedish Production 2020 presented industry and academia's shared vision of what Swedish manufacturing industries would look like in 2020, setting out the basis for a manufacturing research strategy and the priorities needed to meet this vision.

Teknikföretagen – the Association of Swedish Engineering Industries – initiated the development of the Swedish Production 2020 agenda through its 'Production Forum' network. Teknikföretagen's production members first identified a series of critical global trends and challenges facing Swedish manufacturing industries and the implications for the future of their sectors. This analysis was followed up with a questionnaire to member companies designed to identify relevant areas of research in the Swedish manufacturing industry. Swerea IVF – the Swedish Research Institute for Manufacturing R&D and Training – contributed to this analysis on behalf of the industrial research institutes. In a parallel exercise, the Swedish Production Academy (of leading manufacturing research professors) identified important emerging research domains and challenges, from its perspective, at its 2007 Swedish production Symposium,focusing on research areas where Sweden has particular strengths and potential. From these two exercises, a combined long list of potential research areas was created, which was then narrowed down by a set of representatives from key industries, leading Swedish production professors, and representatives from the manufacturing-related research institutes. The final outcome of this process was a consensus list of 16 prioritised research areas necessary to support the future competitiveness of Sweden's manufacturing industries. These research areas fell under three main categories: production systems; integrated production and product development; manufacturing processes.

This shared vision for Swedish Production 2020 was considered highly influential in making the case for the recent prioritisation of 'production science' as one of the key research themes supported by the Swedish government in the most recent research and innovation bill (discussed above).

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6. China

6.1 Summary

China is one of the world's most important manufacturing nations. It is the greatest global exporter, and the largest producer of steel, automobiles and televisions and a growing number of other products. Growth has been around 10% per annum and manufacturing accounts for around 45% of GDP. High priority has been given to higher education and university-based research in recent years and there is now increasing pressure to facilitate innovation and the creation of indigenous products. There are some concerns among policy makers about the economy's heavy reliance on manufacturing and efforts are being made to stimulate the service sector while continuing to encourage production industries. Our study identified the following as key factors in policy and practice.

Manufacturing industrial efficiency. China has strong policy focus on upgrading its national manufacturing industries using high technologies to enhance industrial efficiency, competitiveness and sustainability of resources. The Chinese manufacturing research base is considered a critical part of this endeavour.

'Independent innovation'. This is the name given to an important policy emphasis on reducing reliance on overseas firms for advanced technologies. Manufacturing-related research is seen as playing an important role in ensuring that applied science and engineering ideas developed within the national research base are translated into China's manufacturing industries. This is a key driver behind China's effort to build its R&D and industrial-innovation infrastructure.

Public investment in research funding is relatively 'top down' in comparison to the UK and other Western economies High level research priorities are identified in national strategies –the majority of public R&D funding is allocated based on targeted calls or direct investment in institutions, rather than in response to 'bottom up' proposals from the research community (although the National Natural Science Foundation does invest in this way; and the State Key Laboratories have growing levels of autonomy).

Emerging and priority themes for manufacturing research reflect the industrial upgrading priorities outlined above and include domains such as: high value materials and components; 'green' resource-efficient and eco-friendly manufacturing; digital and intelligent design and manufacturing; design, production and testing technologies for manufacturing at the micro- and nano-scale; and advanced automation and intelligent service robots.

China has a complex manufacturing research and innovation system involving universities, Institutes of the Chinese Academy of Sciences, a variety of government ministries, key laboratories, national engineering research centres, national university science parks. There are also a variety of regional institutes and initiatives, with significant variation between provinces in quality and quantity of R&D activities.

Manufacturing research capabilities and structures are in a state of transition. There is significant policy effort to, for example: strengthen the connections between leading universities and business enterprises; enhance links and cooperation between research institutes; modernize many of the traditional institutes; enhance the innovation and enterprise of R&D centres and institutes; raise the levels of enterprise investment in research institutes; accelerate the translation of S&T research findings into industry.

Chinese policy makers (and the research base) have typically used a relatively narrow definition and emphases in manufacturing research focusing on physical process and production engineering (associated with high volume, low cost sectors). These emphases reflect the historical remits of key institutes, which have tended to reinforce the primacy of traditional manufacturing-related research domains. There is, however, an increasing broadening of manufacturing research, addressing the manufacturability of novel materials, nano- and biotechnologies, and other new challenges.

China has particular strengths in the development end of the manufacturing R&D spectrum. In particular, there is growing competency in prototyping, test beds, and linkages to 'shop floor'. Furthermore, even within the science and technology portion of the Chinese research portfolio, there is significant emphasis on the 'industrialization of S&T', which often addresses manufacturing-related engineering challenges.

The Chinese research base is rapidly becoming more globally connected. This is due to a range of factors, not least: the return to China of Western educated engineers and scientists; proactive international networking initiatives of Chinese and International research agencies. The importance of Chinese manufacturing industries has led several important international manufacturing research centres to make significant efforts to connect with Chinese partners.

6.2 Key manufacturing-related S&T policies and priorities

Despite the importance of China to global manufacturing industries, policy makers acknowledge that the national manufacturing technology base still has relatively limited innovation capability, focusing on primarily low-end products, and involving high levels of resource consumption. Consequently, there has been significant policy focus on research activities designed to upgrade manufacturing industries using high technologies. These and other priorities are discussed in more detail below.

6.2.1 The 'MLP' (Medium- and Long-term National Plan for Science and Technology Development 2006–20)

The Medium- and Long-term National Plan for Science and Technology Development outlines ten prioritised fields, each of which has a set of associated prioritised research topics). One of the priority fields is 'manufacturing technologies', which has eight associated prioritised research topics:

1. Basic and generic parts and components.
2. Digital and intelligent design and manufacturing.
3. Green, automated process industry and corresponding equipment.

4. Recycling iron and steel process techniques and equipment.
5. Large-scale marine engineering technologies and equipment.
6. Basic raw materials.
7. Next-generation information functional materials and components.
8. Key accessory materials and engineering processes for the defence industry.

The 2006–20 MLP also identifies a further eight 'frontier technologies' for priority funding. One of these domains is 'advanced manufacturing technologies', containing the priority topics of:

- extreme manufacturing technology
- intelligent service robots
- service life prediction technologies

Furthermore, the MLP identifies critical aspects of future advanced manufacturing technology needs, including: increased information-intensive performance; the manufacturing of components and systems at extreme scales (e.g. nano-manufacturing or giant industrial engineering systems); environmental friendliness. Consequently, investments in advanced manufacturing research are focused on challenges associated with issues such as extreme manufacturing technology, system integration, coordination technologies, intelligent manufacturing and application technology, high reliability-based large sophisticated systems and equipment design technology.

It should be noted that other MLP prioritised fields, frontier technologies and research topics also involve manufacturing-relevant research. Examples include: new-generation Industrial biotechnology; advanced materials technology (breakthroughs in material design, assessing, and characterizing, and in advanced manufacturing and processing technologies). The broader emphasis on the 'industrialization of S&T' means that a broad range of investments may address manufacturability research challenges associated with particular applied science and engineering research fields.

6.2.2 Innovation roadmap 2050

In 2009 the Chinese Academy of Sciences published the report 'Technological Revolution and China's Future-Innovation 2050', a roadmap for Chinese S&T development to provide additional guidance beyond the MLP. It is anticipated that this roadmap will be updated every four years. The roadmap identifies eight S&T-supported socio-economic systems for development, including a 'sustainable energy and resources system' and 'new materials and green manufacturing system'. Over 300 CAS researchers and experts worked for over a year to analyse socio-economic challenges facing China, consult key stakeholders and gather materials before compiling the report. Although the CAS study is not an official national strategy, it does offer a useful snapshot of current trends, challenges and priorities. The CAS report identifies 22 strategic technology issues that are perceived to be critical to China's future innovation needs, including manufacturing-related topics such as: 'green manufacture of high quality elementary raw materials', synthetic biology, and nanotechnology. More specifically, the CAS roadmapping process also generated an 'Advanced Manufacturing Technology' roadmap. This report highlights key trends relevant to future manufacturing research, in particular: globalization, integration of ICT, 'intelligent' manufacturing systems, resource-efficient production, and the integration of multiple applied science and engineering disciplines to address manufacturing challenges.

6.3 Research emphases (and definition) of manufacturing and manufacturing research

'Manufacturing' in China typically refers to physical production, fabrication and processing activities. Consequently 'manufacturing research' is generally associated with research within traditional academic disciplines, such as mechanical engineering and manufacturing engineering science. However, in response to emerging challenges and trends facing Chinese manufacturing industries 'manufacturing research' is gradually becoming more interdisciplinary and a significant amount of manufacturing-relevant research involves aspects of materials science and engineering, biology, computer science/ICT and 'softer' management science research domains. The key national S&T policy documents (discussed below) not only identify traditional domains (e.g. lean manufacturing, heavy equipment, manufacturing automation, etc), but also acknowledge challenges associated with the manufacturability of novel science-based technologies (e.g. 'biomanufacturing', 'nano-manufacturing') as well as the importance of manufacturing strategy and industrial policy.

6.4 Transforming the research and innovation system

The Chinese innovation system is undergoing a significant period of transition, with important changes being implemented in terms of policies, programmes and institutional structures. In particular, national research policy is increasingly focused on building and upgrading the research infrastructure, for example: converting traditional public research institutes into independent market-oriented research and technology organizations (or merging them with universities); developing R&D programme and policy evaluation processes; increasing the level of R&D carried out by business enterprises. Although private sector research activities are increasing in China, government-involved industrial R&D remains predominant.

Traditionally, universities, research institutes and enterprises have been 'siloed'– carrying out distinct functions within the research and innovation system. There are significant policy efforts underway to connect the activities of the different actors. In particular, there is increasing policy interest in combining resources and expertise of universities, research institutes, and enterprises in such a way that they can use their core strengths to tackle 'bottlenecks' in industrial innovation and technological upgrading.

6.5 Key funding agencies, programmes and policy bodies

The Chinese manufacturing research landscape is embedded in a complex innovation ecosystem of research funders and research performing organizations (see Figure 6.1 below).

There are a variety of research performing institutions in China, including: universities, Institutes of the Chinese Academy of Sciences, key laboratories, regional/provincial institutes and centres, and a growing number of R&D operations run by business enterprises.

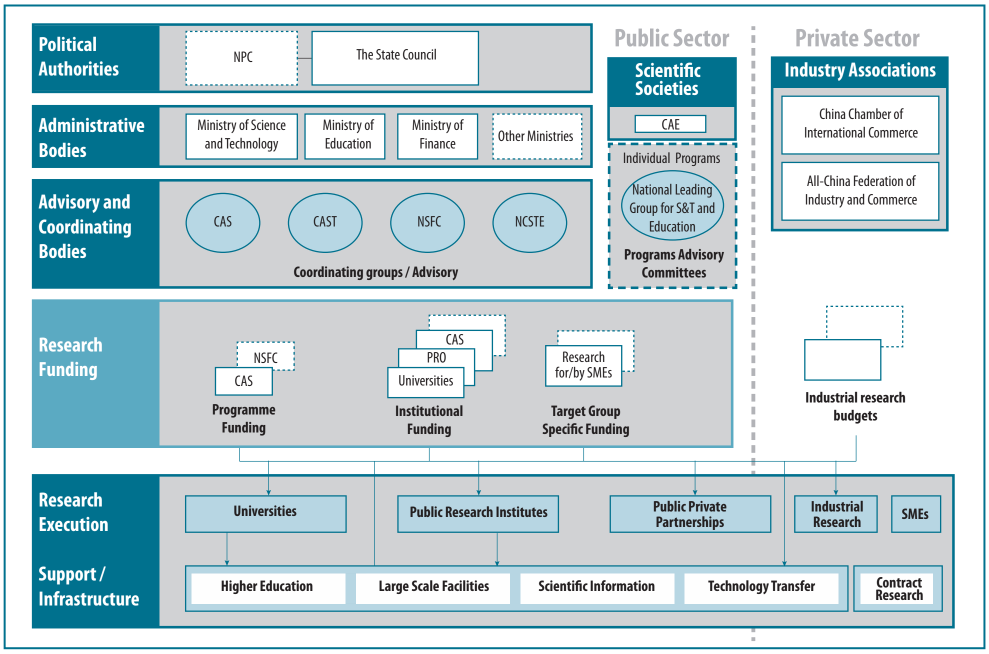

Figure 6.1: Relevant decision-making structures of the Chinese National Innovation System [Proneos, 2010]

The main Chinese ministries and agencies investing in manufacturing-related research – the Ministry of Science and Technology, the National Natural Science Foundation of China, and the Chinese Academy of Sciences – are discussed in more detail below.

Other important stakeholders include: the Ministry of Education, which supports university-based research infrastructure (although it does not award research grants); the State Commission of Science, Technology and Industry for National Defense (COSTIND) which has research portfolio that includes related defence manufacturing engineering research; the Chinese Academy of Engineering. Although not a major research funder like CAS, the latter is an influential learned society whose members include leading Chinese manufacturing engineering researchers.

6.5.1 The Ministry of Science and Technology (MOST)

The Ministry of Science and Technology is probably the largest funder of research in China. The greatest part of MOST's research investments are made through a number of key programmes:

- The National High Tech R&D Program ('863 programme'[1]) includes R&D investments in new materials and sustainability research
- The National Key Technologies R&D Programme includes investments in critical need advanced science and engineering-based technologies
- The National Basic Research Program ('973 Programme') includes materials science and synthesis processes

Broadly speaking, important MOST research funding programmes and institution structures correspond to stages of research maturity, for example:

[1] The '863 Programme' is so called because it was formulated and approved during March 1986. Similarly the '973 Programme' was launched in March 1997.

- State Key Laboratories carry out 'basic' research
- National Engineering Centres carry out 'technology research'
- Technology Innovation Centres (in cooperation with enterprises) carry out application development activities

Few research funding mechanisms directly target the translation of knowledge between centre types or programmes. Nevertheless, within the university system the boundaries between basic, applied and technology innovation/integration research appear more fluid. In particular, research professors are often engaged in a spectrum of research activities (with different levels of technological maturity and user focus): applied technological R&D as well the underpinning applied science or engineering, and even technological system-integration activities with industry.

6.5.2 National Natural Science Foundation of China (NSFC)

The National Natural Science Foundation of China is, perhaps, the closest analogue to the UK research councils, investing in 'bottom up' peer-reviewed research proposals submitted by the research community. Such research grants are, however, typically small relative to other national research programmes.

The main NNSFC division investing in manufacturing research is 'Engineering and Materials Science', but other divisions, such as Information Science and Management Science, also invest in manufacturing-related research.

6.5.3 The Chinese Academy of Sciences (CAS)

The Chinese Academy of Sciences is an influential actor within the Chinese innovation system. Uniquely among academies, the CAS President has a cabinet level position; and the academy is also a significant funder of research in China in its own right. CAS invests in a range of research across its network of Institutes, which cover a broad range of science and engineering research domains. CAS' manufacturing-related Institutes include: the Institute of Process Engineering, Institute of Automation, Institute of Metals Research, Institute of Mechanics, and Institute of Material Technology and Engineering.

CAS also engages in a range of policy analysis activities, e.g. the series of 2050 Roadmaps mentioned above. Even though such studies are primarily intended to inform the Academy's own strategies and priorities, they provide a useful insight into challenges and opportunities perceived by key research and innovation stakeholders in China.

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7. Japan

7.1 Summary

Japan is one the world's most sophisticated manufacturing nations with world-leading products in a range of industries, notably automotive and electronics. Japanese manufacturing firms also excel in managing complex global industrial network and in sophisticated integration engineering. There is also a strong cultural association with manufacturing, reflected in the recognition of, and admiration for, 'monozukuri' – roughly speaking, a celebration of high quality craft and production skills. Compared with many Western countries, Japan's manufacturing R&D investment is more strongly focused within companies than universities. Japanese policy makers and industry are also making significant efforts to address environmental and sustainability challenges, with policies and advanced practices in 'green' manufacturing. Some of these emphases, strengths, and priorities are reflected in the public manufacturing research themes, priorities and approaches described below.

Japanese strengths in manufacturing include a high quality technician skills base; advanced technologies to save energy and resources; a high concentration of advanced component industries; a high quality sophisticated SME base. Other advantages identified by some Japanese and international manufacturing leaders included: a very high level of inter-firm collaboration; a demanding customer base (with very high expectations regarding the quality of products); and a sophisticated global approach to analysing value chains.

Aspects of Japanese manufacturing capabilities which policy makers are looking to strengthen include marketing and planning competencies, the basic S&T research base (and associated opportunities to gain an early leadership position in the manufacturing of emerging science-based technologies), environmental technology regulation, and management of human and knowledge resources within large complex manufacturing projects.

Barriers to coordination and translation of manufacturing research knowledge. There are relatively low levels of interaction between universities and national institutes and industry – universities are primarily funded via the 'basic' research category of the government's S&T Plan, whereas National Institutes are primarily funded via the category for policy-oriented R&D.

Relatively little interaction between 'softer' operational and management research disciplines and physical production technologies or process research was noted in comparison with other leading manufacturing countries (in particular the US).

Researcher mobility. There is relatively little mobility between university or public institute researchers and industry. However, there are a growing number of initiatives to facilitate individual manufacturing firm staff members to spend time on university campuses. New institutional structures (e.g. graduate schools or research centres) are also enabling universities to hire staff with manufacturing industry practice experience.

Manufacturing research strengths. Japan's university-based manufacturing research community has particular strengths in areas such as: materials processing, coatings and films; mechanical engineering and robotics.

Green innovation and manufacturing research. Sustainable manufacturing is highlighted as an important manufacturing research priority, in particular research activities addressing energy conservation in the manufacturing process; and eco-friendly, resource-efficient manufacturing technologies. 'Green Innovation' is one of the two high level priority themes in the new 4th Basic S&T plan, with manufacturing research playing an important role in addressing green innovation challenges.

Other priority manufacturing research areas highlighted by stakeholders included: enhancement of production technologies with IT; manufacturing technologies for biomanufacturing/biotechnology; robotics and other manufacturing technologies appropriate to changing demographics (especially an aging manufacturing workforce); and advanced measurement and analysis technologies for manufacturing.

7.2 Context: The concept of 'monozukuri'

In Japan 'manufacturing research' is often translated as 'monozukuri research'. This translation, however, does not convey the full sense of this uniquely Japanese concept. In Japanese, the words mono (thing) and zukuri (process of making), literally combine to mean the process of making things. But the term monozukuri has accrued an almost spiritual sense associated with the desire to craft excellent products and an ability and pride in constantly striving to improve a production systems, processes and craftsmanship.

Traditionally, the concept of monozukuri has been most readily associated with the material processing and/or mechanical production activities (often carried out by smaller firms) in which Japan has excelled.

Despite some suggestions that this sense of monozukuri is, in fact, a relatively modern concept [Tsai, 2006] which has been promoted to address the perceived de-industrialization of the Japanese economy, monozukuri is nevertheless taken very seriously and features prominently within national science and technology policy initiatives. Increasingly, policymakers and academics are adopting an extended definition of monozukuri which encompasses an extended product development flow – from research and testing through planning, prototyping to manufacturing, distribution, and maintenance, all the way to recycling/end-of-life management. According to Professor Takahiro Fujimoto, Director of monozukuri Management Research Centre at the University of Tokyo, monozukuri describes not only physical production activities, but also product development and the processes by which products reach shelves – a broader term for the total value creation generated from the extended process.

7.3 Context: Japanese industrial innovation policies

7.3.1 National policies for manufacturing research

Insight into Japanese thinking on (and prioritisation of) manufacturing research can be gained from examining its role within the national 'Science and Technology Basic Plan'.

7.3.2 Monozukuri in the Japanese S&T Basic Plan

The Japanese government places significant emphasis on the role of science and technology in contributing to the development of the economy and society in Japan. This is motivated in no small part by the awareness that Japan has limited natural resources and an aging population. Every five years a 'Science and Technology Basic Plan' is designed, based on an S&T' Basic Law'. In particular, this builds on the work of the Council for Science and Technology Policy (CSTP, outlined below).

Enhancing the competitiveness of Japan's manufacturing sectors is an important aspect of the 3rd Basic S&T Plan (2006–10), as evidenced by the repeated references to 'manufacturing', not least the clearly stated goal to 'become the world's top manufacturing nation'. The 3rd Basic S&T Plan has eight 'Promotion Areas' including 'monozukuri (manufacturing) technology'. In the context of the S&T Basic Plan, 'monozukuri technology' addresses not only the development of technologies for manufacturing, but is also focused on optimising added value by extending to service and information technology industries.

The CSTP takes care to emphasize the ongoing importance of manufacturing, pointing to factors such as the large spillover effect to the economy (twice as large as for service industries) and its added value to Japanese exports (~90%). CSTP also highlights Japan's significant advantages in manufacturing, for example: high quality technician skills base; technologies to save energy and resources; concentration of advanced component industries; high quality sophisticated SME base; highly demanding Japanese customer base.

Despite an ostensibly broad definition of monozukuri, most documentation implies an emphasis on physical production and/or materials processing related to components manufacture or mechanical systems assembly. There seems some evidence, however, that research challenges within other priority areas also address 'manufacturing', for example, research related to the production of life science, nanoscience, and space technology products.

7.3.3 METI technology roadmaps

The technology roadmapping analysis issued by METI (managed by NEDO), which identifies important categories of technology, has identified 'systems and new manufacturing (including design, production and manufacturing process) and 'fusion technologies' (including sustainable manufacturing) as some of the major priorities.

7.4 Key funding agencies and manufacturing research stakeholders

Most manufacturing-related portfolios include the universities and the National Institute of Advanced Industrial Science and Technology (AIST). Japan also has a network of industrial research institutes supported at regional level, such as the Tokyo Metropolitan Industrial Research Institute.

The two main government ministries which invest in manufacturing-related R&D are the Ministry of Education, Culture, Sports, Science and Technology (and some its funding agencies: the Japan Society for the Promotion of Science and the Japan Science and Technology Agency), and the Ministry of Economy, Trade and Industry (and one of its funding agencies, the New Energy and Industrial Technology Development Organization).

The relationships between these ministries, agencies and research organizations are summarized in Figure 7.1. The role and activities of some of the key actors are summarized below.

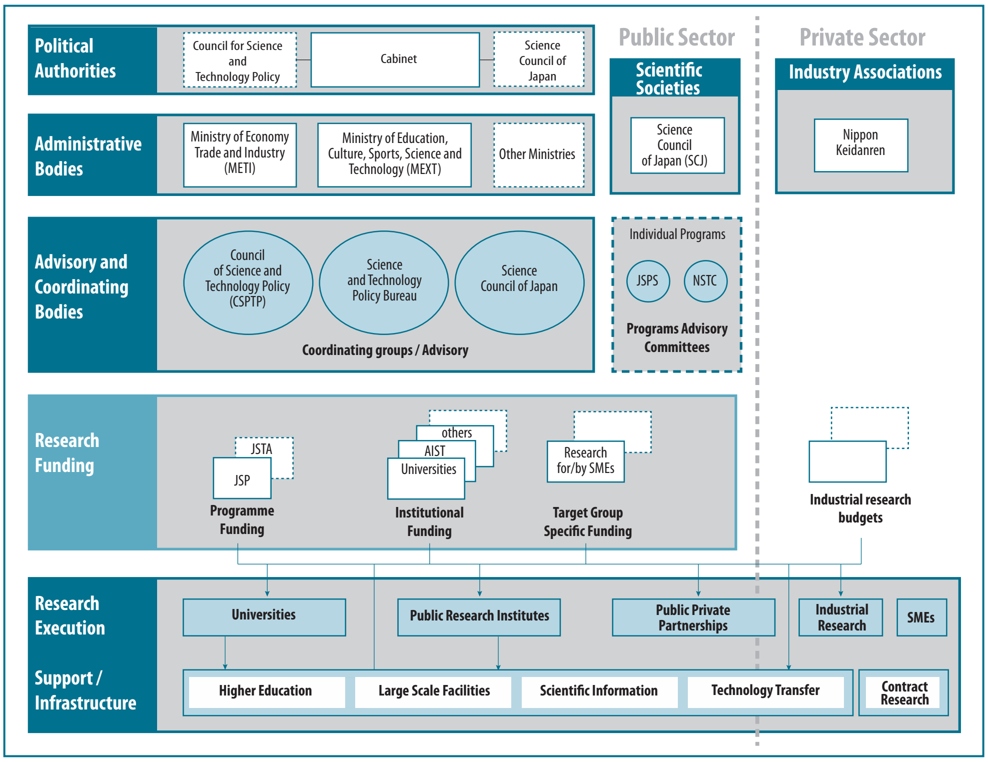

Figure 7.1: Schematic representing Japanese governmental research investment [Proneos, 2010b]

7.4.1 The Japan Society for the Promotion of Science (JSPS)

The Japan Society for the Promotion of Science, JSPS (also known as 'Gakushin') is an independent national agency whose mission is to advance science in all domains of the natural sciences, and the humanities and social sciences. JSPS has a budget of over ¥225B (~£1.5B). Some key programmes includeKAKENHI: Grants-in-Aid for Scientific Research and Research Fellowships for Young Scientists.

Although the JSPS does not run manufacturing-specific national research centre programmes (cf UK Innovative Manufacturing Research Centres)the 21st Century Centres of Excellence Programme has a small number of manufacturing-relevant investments, for example, the Monozukuri Management Research Centre at the University of Tokyo and the 'Nano Factory' centre at Meijo University.

7.4.2 The Japan Science and Technology Agency (JST)

The Japan Science and Technology Agency has a mission to: facilitate innovation based on S&T, through the development of networks between academia and industry; support the career development and research activities of personnel engaged in advancing and deploying S&T; advance S&T for sustainable development. JST has a budget of over ¥115B (~£0.8B).

Some key programmes include:

- CREST (Core Research of Evolutional Science and Technology)
- PRESTO (Precursory Research for Embryonic Science and Technology)
- ERATO (Exploratory Research for Advanced Technology)

7.4.3 The New Energy and Industrial Technology Development Organization (NEDO)

The New Energy and Industrial Technology Development Organization supports R&D for industrial, energy and environmental technologies. NEDO has a dual mission to enhance Japan's industrial competitiveness and address key energy and global environmental challenges. NEDO's budget for its industrial technology development activities is over ¥144B (~£1B).

Key activities include:

- national projects (medium- to long-term high-risk projects requiring industry, government, and academic collaboration; seven domains, including 'new manufacturing technology')
- practical application by enterprises (economic stimulus support for R&D close to practical application)
- Technology Seed Grants (research grants to universities and research institutes for discovery of 'technology seeds' with potential to address future industrial needs)

7.4.4 Ministry of Education, Culture, Sports, Science and Technology (MEXT)

The Ministry of Education, Culture, Sports, Science and Technology controls approximately two thirds of the government budget for science and technology R&D. MEXT is the primary funder of university-based manufacturing-related research, primarily through JST and JSPS.

7.4.5 Ministry of Economy, Trade and Industry (METI)

The Ministry of Economy, Trade and Industry has one major research institute, the National Institute of Advanced Industrial Science and Technology, AIST, as well as the R&D agency, the New Energy and Industrial Development Organization, NEDO (see above). Although much of METI's manufacturing-related research investments are made to firms, some research funds do find their way to the university research base, e.g. via NEDO project funding.

7.4.6 Council for Science and Technology Policy, Cabinet Office (CSTP)

The Council for Science and Technology Policy acts as a 'command centre' for national integrated efforts to advance science and technology (S&T) in a coherent, comprehensive and planned manner – not only to facilitate the effective development of innovative technologies, products and services underpinning a healthy industrial economy, but also to enable the strategic deployment of S&T to solve important societal challenges (e.g. energy, water and infectious disease issues). Central to S&T policy in Japan are the series of 'S&T Basic Plans'. The manufacturing-related research priorities of the

3rd Basic S&T Plan are discussed briefly above. Full details of 4th S&T Basic Plan are expected to be announced shortly.

7.5 Key research performing organizations

7.5.1 National Institute of Advanced Industrial Science and Technology (AIST)

AIST is METI's largest research institute. Its individual research units are given significant autonomy within a somewhat flexible organisational structure. AIST research units are broadly categorized to three main types: fixed lifetime research centres (typically seven years) with clear research goals; research institutes which are more 'bottom-up' and address the mid- and long-term strategies of AIST, including the development of emerging technologies; and research initiatives – smaller, fixed-term units conducting specific (often multidisciplinary) research projects.

AIST carries out a significant amount of manufacturing-related R&D. Much of AIST's manufacturing-related research takes place within the Advanced Manufacturing Research Institute (AMRI) – one of AIST's main research laboratories. Other major manufacturing-related activities include the Digital Manufacturing Research Centre and the Intelligent Systems Research Institute. AIST also addresses manufacturing-related challenges of emerging technologies, such as biomaterial production technologies and nanomanufacturing.

7.5.2 The Japanese university system

The Japanese public research system has changed significantly since the 1990s. Previously, the system was characterized by a relatively low contribution to national R&D activity by Japanese universities (compared with other major OECD economies). The research funds that were invested in universities came primarily through formula-based research funding awarded to institutions, rather than competitive research grant programmes. Furthermore, there was very little interaction between national universities and industry, although the level of engagement between engineering faculty and manufacturing firms was higher than in other domains. Much of Japan's public manufacturing industry-relevant research was carried out at AIST. Consequently, there has been relatively little private sector funding of university-based research.

Key public research system reforms and related initiatives that have taken place over the last decade or so include the establishment (in 2001) of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and the establishment of the Council for Science and Technology policy to formulate and coordinate S&T policy across all ministries. The series of five-year Basic Science and Technology Plans (discussed above) addressed not only governmental R&D investment and prioritisation, but also reforms of the public research and innovation system. These included the incorporation of Japanese universities and public research institutes, giving greater autonomy and opportunities to engage with industry.

These reforms notwithstanding, while private sector investment in public research institutions is rising, it remains low compared with that of some other leading manufacturing research nations.

7.5.3 Regional industrial research institutes

Regional (prefectural or municipal) industrial research institutes support applied research and development activities within regional economies and communities. They typically feature well-equipped research laboratories, characterization and testing facilities. They also provide consulting support, technical information, seminars, and courses for local industry. Institutes are often co-located with other regional industry support services, including business planning and operations consulting. An example of a metropolitan industrial research institute is discussed below.

Tokyo Metropolitan Industrial Research Institute (TIRI)

The Tokyo Metropolitan Industrial Research Institute activities are focused on supporting the production and technical competences of small and medium enterprises in the Tokyo metropolitan area, with particular emphasis on needs-oriented activities, strategic planning and industrialization. TIRI's activities include not only support for R&D and technical assistance, but also support for product development and technical management.

Many of TIRI's activities have evolved to meet the needs of the SMEs in Ōta City – one of 23 special wards within the metropolitan prefecture of Tokyo – which is home to over 5000 companies, many of which are small- and medium-sized metalwork and mechanics enterprises using precision technologies and high-level craftsmanship to provide products for Japan's manufacturing sector. Although the concentration of factories, highly networked nature of the local industrial base and high level of skills of local craftsmen and technicians is a significant strength of Ōta City, the aging of the skilled workforce and changes to the industrial structure pose a significant threat to Ōta City's ongoing industrial competitiveness. Industrial policy towards manufacturing in Ōta City focuses on the promotion of core technological competencies and skills, together with the promotion of management skills (including strategy, business models and marketing). Industry within Ōta City is supported by the Economic Development Division of the local government, which hosts a range of business support activities in addition to its support for TIRI

TIRI has a research staff of over 200, including about 80 PhDs. The Institute's R&D programmes include: 'basic research' activities addressing problems in industry; 'joint research' collaborations between TIRI staff and SMEs in technology and product development; and competitively funded national research foundation grants. TIRI's 'Design Centre' undertakes support activities that extend across the entire spectrum from product planning through product design, mechanical design, and pilot manufacture of prototypes. TIRI has a broad range of knowledge, skills, equipment and other infrastructure related to design, modelling fabrication, testing, and production all located in one place. In addition, the Institute hosts a range of seminars that respond directly to the technical needs of the local (and national) industrial base. These seminars bring together not only TIRI's research expertise with SMEs, but also involve the academic research base and other expertise as necessary. TIRI's activities complement those of national institutes (e.g. AIST) by interacting with companies at a very practical and direct needs-based level.

7.5.4 Colleges of Technology

Although predominantly education and training institutions, it is worth noting the high level of interaction between manufacturing SMEs and the Japanese 'kōsen' (Colleges of Technology) system. Colleges of Technology typically run five-year courses (post GCSE/junior high school) which offer in-depth learning in specialized technical disciplines to prepare students for employment, primarily as engineers in development, design or production engineering sections of manufacturing firms.

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8. Concluding observations

8.1 Introduction

This study set out to explore international approaches to manufacturing research; identifying key national actors, prioritised research domains, and effective practices for translating manufacturing research into industry. The report also examined the broader national R&D funding and industrial contexts within which the main manufacturing research funding agencies and public research-performing organizations operate.

In this Observations chapter, we conclude our report by highlighting some important issues, practices and themes that arose from interviews with international manufacturing research leaders, manufacturing R&D policy makers, and agency programme directors; as well as from reviews of the published strategies and reports of federal governments (including relevant ministries and state agencies which support manufacturing-related research and innovation).

The observations outlined below do not necessarily apply to all manufacturing nations considered in this report, but there are, nevertheless, themes and issues which are common to many international manufacturing research communities, as well as notable effective practices implemented within particular countries.

Special attention is given to those international approaches to manufacturing research which appear to contrast most strongly with those in the UK, particularly those which appear to give international manufacturing research communities (and those industries which they support) significant competitive advantage. Aspects of manufacturing research practices, policies, or programmes where there may be scope for the UK to enhance its competitiveness through new or adapted approaches to manufacturing research are highlighted (in italics).

8.2 International approaches to manufacturing research: Key issues, practices, themes and potential sources of competitive advantage

Policy interest in manufacturing research

1. There is increasing focus by policy makers in all countries on the potential of manufacturing research to enhance industrial competitiveness. This attention reflects a broader renewal of interest in the role of manufacturing itself within national economies.

2. The frontiers of manufacturing research are being shaped by fundamental changes in the nature of manufacturing. In particular, there is significant interest in the potential of manufacturing research to address the challenges and opportunities created by: the increasingly complex and globalized nature of industrial systems; accelerating technological innovation; and the growing need for resource-efficient production.

3. There is a growing awareness among policy makers of the potential of manufacturing innovation to contribute to tackling a range of key social, economic and environmental 'grand challenges' such as healthcare, sustainability, mobility and security.

Industrial innovation ecosystems

4. There are important differences between the industrial innovation 'ecosystems' of different countries. The different innovation actors – universities, intermediate research institutes, government ministries, R&D agencies, industry associations, and others – vary significantly in their configuration and missions, as well in the scale and scope of their activities, and their interconnectedness. This systems context should be an important consideration when exploring opportunities to transfer or adapt particular manufacturing research practices, programmes, or institutional structures for the UK. Furthermore, the actors within some national manufacturing research systems appear better aligned and coordinated (e.g. EDB, A*STAR, NRF and HEIs in Singapore) and/or there are proactive efforts to enhance interagency alignment through initiatives to build holistic national manufacturing innovation infrastructure (as evidenced by the recent US inter-agency 'Extreme Manufacturing' workshop hosted by NIST).

   There are opportunities for UK manufacturing research funders (and other stakeholders) to more fully reflect the system-nature of the UK manufacturing research landscape in the design of their manufacturing research strategies, programmes and portfolios. In particular, there may be opportunities to enhance interagency alignment and develop joint initiatives to build a more 'holistic' national manufacturing innovation infrastructure.

5. There appears to be significant variation between the manufacturing research portfolios of different nations, i.e. varying levels of investment, scale of activities, and international competitiveness across different manufacturing research domains, (such as materials processing, production tools and technologies, manufacturing systems engineering and operations research).

6. There are significant variations in how the term 'manufacturing research' is used in different countries. Such semantic differences reflect national industrial strengths and innovation priorities. The perceived boundaries associated with 'manufacturing research' may vary in terms of: relevant academic disciplines, industrial sectors and systems impacted, as well as levels of technological and industrial maturity. There is thus considerable scope for misinterpretation and care should be taken in interpreting many international policy documents and analyses of research portfolios. Furthermore, several international manufacturing research leaders suggested that narrow 'traditional' definitions of manufacturing research become enshrined in organisational structures, budgets and review processes of funders, inhibiting initiatives from taking on truly multidisciplinary manufacturing research challenges (e.g. sustainable manufacturing) which require a broad spectrum of research expertise and stakeholder engagement.

People, skills and leadership

7. In some countries, most notably in Germany, many academic manufacturing research leaders have significant levels of industrial experience. Such leadership

experience appears to make a major contribution to integrated research activities addressing complex manufacturing user challenges.

UK manufacturing R&D funders should explore mechanisms for manufacturing research leaders with significant industry experience to participate in important research programmes (e.g. within user challenge-based initiatives such as ESPRC's Centres for Innovative Manufacturing).The EPSRC's proposed Manufacturing Fellowships programme may offer an extremely useful opportunity in this regard.

8. There appears to be greater emphasis in some leading manufacturing nations on the importance of producing engineering PhD students for the manufacturing workforce. Training PhD students who would become the 'manufacturing leaders of the future' was regularly cited as one of the main outputs – if not the main output – of public investment in manufacturing R&D. In some cases there was a more explicit focus on ensuring that the next generation of manufacturing leaders have experience and expertise at the frontiers of advanced manufacturing innovation. In Germany, great importance is placed on giving these production engineering graduate students significant and varied industry problem-solving experience. It is worth noting that many of the goals and characteristics of the EPSRC EngD and industrial doctorate centres programme are supported by international experiences and by practices highlighted by international manufacturing research leaders.

   Consideration should be given to the appropriate fraction of Engineering Doctorate (EngD) studentships within the overall cohort of PhD students working on manufacturing-related research. There may be potential competitive advantage and enhanced industrial impact to be gained from providing a greater number of manufacturing engineering PhDs with more substantial (and varied) manufacturing industry project experience.

   It may also be worth exploring the potential for UK intermediate research institutes (e.g. manufacturing-related Technology Innovation Centres) to facilitate EngD engagement in real-world manufacturing engineering problem-solving.

9. The manufacturing engineering research activities of many international universities are both complemented by and leverage the expertise, facilities and networks of other manufacturing-related research and technology organizations within their national innovation system (e.g. Fraunhofer Institutes in Germany, AIST in Japan, SIMTech in Singapore).

   There is a strong case for synergistic engagement between the university manufacturing research base and intermediate research and technology organizations (e.g. Centres for Innovative Manufacturing and relevant Technology Innovation Centres). In particular, there may be potential in exploring opportunities for joint research programmes, researcher mobility initiatives, shared equipment programmes, and PhD/EngD industry engagement opportunities.

10. There are significant variations between nations in the degree to which 'real-world' industry problem-solving research is carried out in universities. This partly reflects variations in national manufacturing research 'ecosystems', where problem-solving 'contract' research is distributed differently across universities, national laboratories, research and technology organisations (RTOs) and other intermediate institutions. In some countries, most notably the US, concern was expressed by several academic manufacturing research leaders that there had been too great a decline in 'traditional

industry problem-solving' within university engineering departments – some arguing that too much 'real engineering' was being replaced by 'engineering science'. And that the consequences of this more general engineering-wide phenomenon were especially acute for manufacturing research where industrial connectedness necessarily extends beyond industrial R&D divisions to address challenges in real world production operations and across the manufacturing value chain.

UK manufacturing research stakeholders should explore approaches to assessing manufacturing-related engineering research which ensures that responsive industrial user engagement (and problem-solving) is appropriately valued.

In particular, there may be value in examining tenure processes, reviewer selection protocols and grant funding criteria, etc, to ensure an environment which supports a UK manufacturing research portfolio with an appropriate balance of 'engineering science', industry engagement and problem-solving activities for manufacturing firms.

Manufacturing research: Multidisciplinary, systems-based and global

11. Many international R&D funders put significant emphasis on the multidisciplinary nature of manufacturing research. In managing manufacturing research portfolios and designing research programmes, particular attention is paid to mechanisms that break down barriers between traditional production engineering disciplines and other research domains. While this issue is applicable to all multidisciplinary research, there is concern among some manufacturing research leaders in several countries about the 'siloed' nature of some manufacturing research organisational structures and communities. There is a perception that there is suboptimal interaction between disciplinary, national and/or industrial communities addressing aspects of the same research challenges. 'Sustainable manufacturing' was regularly cited as an example in this regard.

12. There is an increasing emphasis in many countries on the systems-nature of many manufacturing research challenges (and the importance of 'systems perspectives' or 'whole systems approaches' to addressing them). A significant fraction of international manufacturing research is funded through systems-related engineering programmes; and is carried out within the industrial or engineering systems divisions of university engineering faculties. Many manufacturing leaders, notably in the US, pointed to an emerging field of 'engineering systems' (carefully distinguishing this from systems engineering) which brings together aspects of engineering approaches to technology, management, policy (and even the social sciences) to address a range of industrial and economic challenges, including many related to manufacturing, product development, and industrial engineering.

UK manufacturing research stakeholders should consider the appropriate mix of funding mechanisms, project sizes and metrics for addressing a manufacturing research portfolio which will become increasingly multidisciplinary and systems-like in nature. Particular attention should be paid to mechanisms with the potential to remove barriers between disciplines, increase mobility and cultivate a 'whole systems' perspective.

13. A significant fraction of new knowledge generated within leading manufacturing research nations – notably Japan and Germany – is disseminated via national (non-

English language) journals and conferences. These dissemination patterns seem to be primarily driven by a motivation to reach industry-based manufacturing engineers operating within local economies. There are concerns, however, that such dissemination practices may inhibit valuable international knowledge exchange and collaboration. Many international manufacturing research stakeholders predicted that non-English-speaking manufacturing research communities will increasing choose to disseminate research findings within the primary international (English-language) research literature.

Manufacturing research centres

14. The structures, activities and goals of university-based manufacturing research centres are strongly influenced by the innovation 'ecosystem' within which they have evolved. For example, the strategies (and sustainability) of many US manufacturing research centres are strongly influenced by research funding opportunities from the Department of Defense; while the scope of research activities within many German research centres are often shaped by the particular strengths and expertise of local Fraunhofer Institutes.

15. The increasingly global nature of manufacturing has influenced the strategies of some international manufacturing research centres and institutes. In particular, some high profile centres are aggressively nurturing their international academic and industrial networks and connectedness.

16. Although there are few manufacturing-specific international manufacturing research programmes (cf the EPSRC Centres for Manufacturing Innovation), those centre programmes that do fund manufacturing centres as part of their portfolio, e.g. the US Engineering Research Center programme, put significant emphasis on highly collaborative, multidisciplinary research.

    Centre programmes, such as the EPSRC's Centres for Innovative Manufacturing (CIM) programme are a critical component of the UK manufacturing research portfolio. Key features of the current CIM model – in particular, the focus on major manufacturing-related user challenges and the emphasis on 'translational' research – are strongly supported by international experiences and practices highlighted by international manufacturing research leaders.

17. Many successful international manufacturing research centres have ex-industry senior practitioner experts in various roles within the leadership team. These individuals often have broad industrial career experience within a range of R&D, production and strategic management roles. Many manufacturing centres emphasize the contribution of such individuals and what they bring to the research endeavour: insights into industrial practice and culture; a network of real-world contacts; as well as operational and management experience that can be invaluable in complex, multi-project, multi-partner R&D endeavours. Of particular value appears to be the high level of trust such individuals engender in engagements with industry partners, often facilitating more substantial, strategic and long-term collaborations. While this issue is applicable to all research centres, international experience suggests it may be particularly important for manufacturing-related centres where insights into practices on the 'shop floor' and across the manufacturing value chain may be especially valuable and impactful.

The background, skills, and expertise of research leaders are a key determinant of the competitiveness, impact and success of manufacturing research centres.

UK manufacturing research funders might usefully explore opportunities to strengthen the review processes of key manufacturing-related centre programmes (and other critical mass initiatives) to give greater scrutiny to whether the full set of skills and expertise necessary to effectively address the declared research challenge have been assembled. In addition to forming teams with an appropriate breadth of disciplinary backgrounds and industry experience and management expertise, consideration should be given to individuals with backgrounds that enable them to help translate research findings ('from discovery to integration').

Manufacturing the future

18. There are some common manufacturing research themes that have been widely identified as priorities for future funding, most notably:

- sustainable, resource-efficient manufacturing
- production technology to exploit the potential of emerging technologies (in particular novel bio- and nano-technologies)
- leveraging simulation and modelling techniques to address manufacturing challenges
- flexible, rapidly responsive production systems for customized manufacturing

19. There is significant focus in many countries on the potential for manufacturing research to support the development of emerging high value industries. In particular, there is a growing perception that manufacturing researchers are especially well placed to addresses the multidisciplinary industrialization challenges of novel emerging S&T-based technologies (e.g. synthetic biology, regenerative medicine, various nanotechnologies).

    UK R&D funders should review their manufacturing and emerging S&T research portfolios to ensure there is an appropriate level of investment in endeavours to address the manufacturability challenges of high potential, high risk emerging technologies and industries.

20. In some countries there are highly systematic approaches to identifying future manufacturing innovation needs, emerging S&T developments, and associated research funding priorities. For example, the German Ministry for Education and Research (BMBF) recently commissioned a substantial study – involving extensive stakeholder consultation, competitor analysis and scenario planning exercises – to inform the selection of manufacturing research funding priorities within Production Research Framework 2020. In Sweden, a similar exercise exploring 'Swedish Production 2020' was driven 'bottom-up' by the manufacturing research community, led by the Swedish Production Academy and the Association of Swedish Engineering Industries.

    Systematic, consultative and forward-looking exercises (including the use of online consultation processes, white papers, national forums, roadmapping/foresight processes, etc) have the potential to improve interactions and awareness between academia and industry; as well as with central government and other innovation agencies.

In particular, there seems to be potential value in stimulating dialogue and debate on: research opportunities and challenges; barriers to translation of research findings; gaps in innovation funding; mutual awareness of academic and industrial capabilities; and opportunities for alignment of policies and programmes.

The UK manufacturing research community (together with relevant public sector and industrial stakeholders) should consider opportunities to engage in structured and systematic explorations of the future challenges facing manufacturing industries together with new insights, technologies and multidisciplinary research domains emerging from the science and engineering base.

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Glossary

ACATECH	German Academy of Science and Engineering
AIF	German Federation of Industrial Associations
AIST	National Institute of Advanced Industrial Science and Technology (Japan)
ARPA-E	Advanced Research Projects Agency-Energy (USA)
ASTAR	Agency for Science, Technology and Research (Singapore)
BMBF	Federal Ministry of Education and Research (Germany)
CAS	Chinese Academy of Sciences
CMMI	Civil, Mechanical and Manufacturing Innovation
CRC	Collaborative Research Centre
DARPA	Defence Advanced Research Projects Agency
DFG	German Research Foundation
DOD	Department of Defence (USA)
DOE	Department of Energy (USA)
EDB	Economic Development Board (Singapore)
EFRC	Energy Frontier Research Centers
EOP	Executive Office of the President (USA)
EPSRC	Engineering and Physical Sciences Research Council
ERC	Engineering Research Center (USA)
FhG	Fraunhofer Society (Germany)
GATech	Georgia Institute of Technology (USA)
GSaME	Graduate School for Advanced Manufacturing Engineering
Fraunhofer IAO	Fraunhofer Institute for Industrial Engineering
IfM	Institute for Manufacturing
ISI	Fraunhofer Insititute for Systems and Innovation research
ITRI	Industrial Technology Research Institute
I/UCRC	Industry/University Cooperative Research Center
IWB	Institute for Machine Tools and Industrial Management
JSPS	Japan Society for the Promotion of Science
JST	Japan Science and Technology Agency
KTH	Royal Institute of Technology (Stockholm, Sweden)
MEL	Manufacturing Engineering Laboratory
MEP	Manufacturing Extension Partnership
METI	Ministry of Economy, Trade and Industry (Japan)
MEXT	Ministry of Education, Culture, Sports, Science and Technology (Japan)

MANTech	Manufacturing Technology Program
MIT	Massachusetts Institute of Technology
MLP	Medium & Long-term National Plan for Science & Technology Development (China)
MNC	Multinational Corporation
MOST	Ministry of Science and Technology (China)
NEDO	New Energy and Industrial Technology Development Organization (Japan)
NAE	National Academy of Engineering (USA)
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
NSFC	National Natural Science Foundation of China
NSTC	National Science and Technology Council (USA)
PCAST	President's Council of Advisors on Science and Technology
PTW	Institute of Production Management, Technology and Machine Tools
RTO	Research and Technology Organisation
RWTH	Rheinisch-Westfaelische Technische Hochschule Aachen (Aachen University)
SEBML	Science and Engineering Beyond Moore's Law
SIMTech	Singapore Institute for Manufacturing Technology
SFF	Swedish Foundation for Strategic Research
SME	Small and Medium Enterprise
STPI	Science and Technology Policy Institute
TIP	Technology Innovation Program
TIRI	Tokyo Metropolitan Industrial Technology Research Institute
VINNOVA	Swedish Governmental Agency for Innovation Systems
VR	Vetenskapsrådet (Swedish Research Council)

Appendix 1: Definitions of manufacturing research

Many of the most important emerging areas of manufacturing research are intrinsically multidisciplinary, systems based, and challenge driven. The frontiers of new science and engineering knowledge with the potential to impact manufacturing productivity are constantly changing. Traditional concepts of manufacturing research – characterized by established industrial sectors or academic disciplines – may no longer be adequate. In this section we explore different dimensions of manufacturing research, including: different manufacturing system levels, the broader manufacturing system context, and the industrial life-cycle. In particular, we discuss the potential for a more comprehensive characterization of manufacturing research to help industrialists, researchers and policy makers to articulate areas of need and challenge more clearly, and to apply new knowledge and future investments with greater precision.

A1.1 Introduction

The frontiers of manufacturing research are being shaped by fundamental changes in the nature of manufacturing itself. In response, many policy makers are showing increased interest in the potential of manufacturing research to address the challenges and opportunities created by the increasingly complex and globalized nature of industrial systems, the accelerating pace of technological innovation and time-to-product, and the growing need for sustainable, resource-efficient production.

These fundamental changes in manufacturing have significant consequences for how we think about the scope and definition of 'manufacturing research'. The increasing systems-complexity of industries and production processes, the potential impact of emerging technologies across multiple sectors, and the growing role of manufacturing research in addressing broader societal challenges are causing many policy makers to rethink the boundaries that surround traditional manufacturing research disciplines and industrial sectors.

As an academic research domain, 'manufacturing research' has traditionally been much less clearly defined and delineated than other science or engineering disciplines. Attempts to characterize manufacturing research are complicated both by the range of academic disciplines that may be deployed to address manufacturing-related research challenges, and by its close engagement and association with a particular set of established industrial sectors (e.g. automotive, steel-making).

Clarity on the definition, scope and dimensions of manufacturing research, however, has important consequences – not least for those government agencies charged with investing in public R&D. In particular, the way in which manufacturing research is characterized is likely to influence portfolio management and investment prioritisation, programme design and proposal review, and interagency engagement and joint initiatives. Furthermore, greater precision in characterizing manufacturing research may enable more targeted, efficient and timely investments in support of industrial innovation and competitive advantage: targeting barriers to the translation of emerging technologies into new processes and products; identifying new ways of delivering products to customers when and where they are most needed, and in an efficient and sustainable way; and exploiting synergies between research communities to address complex, multidisciplinary manufacturing innovation challenges.

A1.2 Dimensions of manufacturing research

There is no established definition of 'manufacturing research'. Definitions vary from stakeholder to stakeholder, and vary in emphasis and scope depending on stakeholder missions and core activities. Interviews with international stakeholders and analysis of manufacturing-related research policy and strategy documents from different countries suggest that different groups discuss, characterize and emphasize aspects of manufacturing research using some or all of the following dimensions:

- academic disciplines
- industrial sectors
- industrial maturity (e.g. as described by industrial or product life-cycle stages)
- manufacturing system-level (i.e. different systems-of-analysis, such as production unit processes, machine tools, factories, manufacturing value chains and industrial sectors)

Although most groups agree on a set of core disciplines, sectors, and industrial systems which are clearly 'manufacturing research'; there are often very different perspectives on how far the scope of manufacturing research extends along each of these dimensions. Some of these variations in perspective and scope are discussed in more detail in the following sections.

A1.3 Academic disciplines

Although traditionally an exclusively engineering discipline (often with its home within university mechanical engineering departments), the multidisciplinary nature of manufacturing research increasingly draws expertise and techniques from a range of domains, depending on the nature of the manufacturing challenge being addressed. Perspectives still vary, however, regarding the disciplinary scope of manufacturing research.

Essentially, all definitions of 'manufacturing research' include the activities of a core set of 'hard' physical production engineering research domains (machine tools, process technology, robotics and assembly, etc).

For some, however, the definition extends so far as to cover systems engineering and operations-related research domains (e.g. control systems, sensors and sensor networks, supply chains and logistics) when applied to manufacturing-specific problems.

Others extend the definition yet further to allow 'softer' (non-engineering) academic disciplines such as management science, economics or even subjects such as psychology, when they are deployed to address manufacturing-related research challenges.

Part of the difficulty in characterizing manufacturing research in terms of an extended set of academic disciplines arises from the fact that researchers in these domains may not naturally identify themselves as manufacturing researchers, even when manufacturing

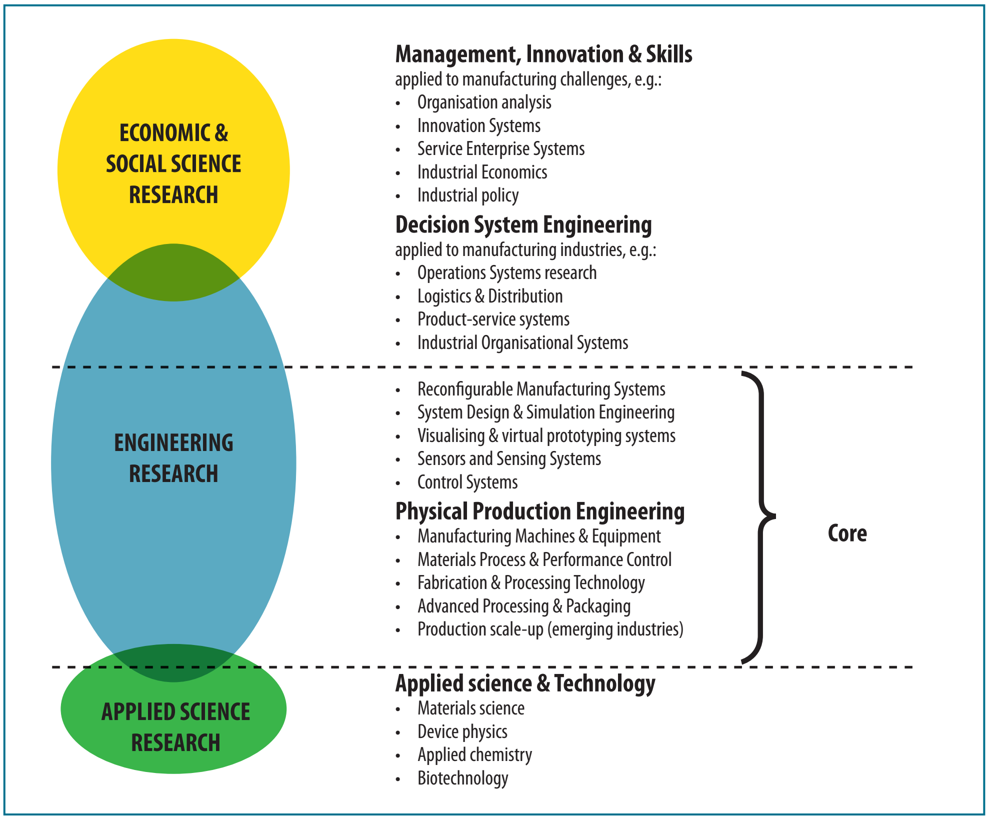

Figure A1.1: Schematic indicating spectrum of potentially manufacturing-related research domains (with illustrative examples). A core set of domains, universally regarded as manufacturing research, is also indicated

is an application domain of interest to them. Systems engineering, for example, makes a hugely significant contribution to many manufacturing research agendas, but systems engineers also address research questions across a range of application domains, such as transport, healthcare provision and telecommunications networks.

A1.4 Manufacturing system unit of analysis

Manufacturing research – set in the context of real-world industrial systems and manufacturing user challenges – is an intrinsically multidisciplinary, systems-based domain. From this perspective, it is useful to categorize manufacturing research in

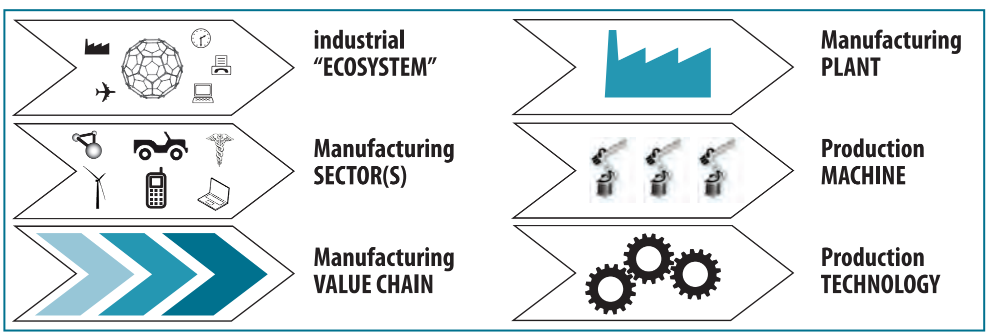

Figure A1.2: Examples of industrial system- or sub-system-levels within which manufacturing research unit-of-analyses (or research challenges) may be most appropriately described.

terms of a hierarchy of manufacturing systems and subsystems that a particular piece of research is addressing.

Again, there are varying perspectives as to the (system-level) units of analysis that constitute manufacturing research. For some, manufacturing research activities are restricted to studying system-levels from production unit processes, to production machines and factories. For others, the systems of analysis include the extended value chains of production-based firms. For others, studies of industrial sectors, complex industrial 'ecosystems', or related government policy are legitimate 'manufacturing research' inquiry.

Nevertheless, a systems approach to characterizing manufacturing research (or defining its scope) has significant advantages. In particular, it may facilitate understanding and awareness of the broader context within which the research challenge is situated in order to appreciate the ultimate industrial (or social) impact of the research endeavour.

A1.5 Industrial sectors

For some stakeholders 'manufacturing research' implies research activities relevant to a narrowly defined 'manufacturing' industrial sector. Within this perspective, manufacturing research is often confined to those research activities relevant to firms engaged in relatively high volume and low skilled manipulation of materials (primarily metals, semiconductors, ceramics, etc). From this viewpoint, 'manufacturing research' implies endeavours to generate new knowledge associated with processing activities such as grinding, coating, forging, casting, moulding, etc. Consequently, 'manufacturing research' is limited to research addressing user challenges within industrial sectors such as: automotive; electronics and microelectronics; industrial materials. Sometimes this definition is extended to other traditional high volume processing industries, such as chemicals and food and drink.

This narrow perspective on what constitutes 'the' manufacturing sector often elevates other production-based industries beyond 'manufacturing'. For some people, for example, biopharmaceutical production is part of the life sciences industry and not 'the manufacturing sector'. The features on which such distinctions seem to be based are sector characteristics which are not easily captured within industry classification codes or industrial value chain stages. For example, factors which lead some people to exclude certain industries from 'the manufacturing sector' include: high levels of systems-complexity (e.g. telecommunication systems); high levels of R&D intensity (e.g. biopharmaceuticals); or novel S&T-based product sectors (e.g. regenerative medicine).

By contrast, for some stakeholders, a sector such as telecommunications is most appropriately called 'advanced manufacturing' (to distinguish it from traditional manufacturing sectors such as chemicals or steel). While for other stakeholders any production-based sectors can be appropriately classified 'manufacturing'.

As part of this review, several international stakeholders suggested that these sector-based semantic differences had very real implications for the 'siloed' nature of 'manufacturing research'. In some instances, narrow definitions of 'manufacturing' can become enshrined in organisational structures, programmes and budgets, resulting in manufacturing engineering researchers becoming distanced from important research challenges associated with important and/or emerging sectors, for example, biopharma, ICT devices.

A1.6 Industrial (product) life-cycles

Manufacturing-based industries are, of course, dynamic systems and uncertainties related to product engineering, design, manufacturability and market acceptance are constantly evolving. Consequently, manufacturing-related sectors have different research and innovation needs at different stages of product and industrial maturity.

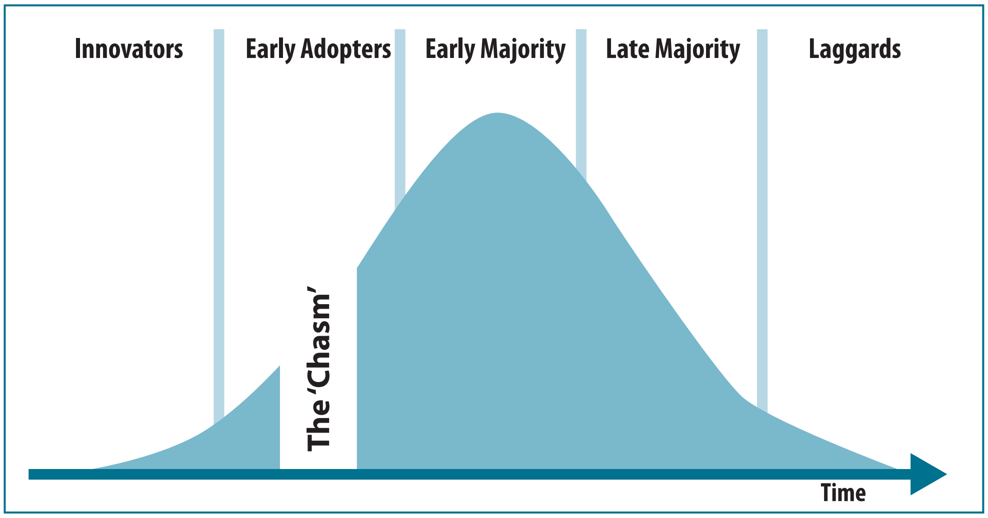

Figure A1.3: Schematic illustrating industrial life cycle with different phases of industrial maturity (product adoption stages)

For some stakeholders, 'manufacturing research' is primarily related to the research challenges of established sectors – i.e. industries with mature production paradigms, product designs, value chains and markets. 'Manufacturing research', in this context, describes those activities that create new knowledge associated with incremental advances in the later, more stable, phases of industrial and product life-cycles.

Some stakeholders make a clear distinction between such manufacturing research activities addressing mature industrial sectors and 'advanced manufacturing research'. Advanced manufacturing research typically refers to research addressing the innovation needs of emerging industries (in particular, research addressing the scale-up and manufacturability challenges of novel technologies) which still have significant uncertainties and risks associated with application performance, dominant design, product unit costs and even market acceptance; or addresses research challenges related to the absorption of disruptive technologies or processes within existing industrial sectors.

In several countries, some policy makers are paying particular attention to the manufacturing research challenges associated with emerging technologies – a domain where the linkages between scientific discovery and manufacturing competitiveness are more closely coupled. Some stakeholders argue that there should be greater portfolio investment further into the 'valley of death'. And that advanced manufacturing research has the potential to accelerate the translation of novel science-based technologies into new high value industries.

New manufacturing research knowledge emerging from the academic 'research value chain' (see below) can impact productivity at any point in the life cycle of a technology or an industry – not just at the early 'innovation' or mature 'late majority' stages (See

Figure A1.3). In particular, manufacturing research can make a contribution to the scale-up challenges of translating novel science-based emerging technologies from the research laboratory into real-world manufacturing environments. There is significant attention in many countries on the potential to enhance the productivity and competitiveness of national manufacturing enterprises through 'faster, better, cheaper' methods for incorporating emerging technological advance (notably novel biotech and nanotech materials) into new processes and products.

A1.7 Innovation life cycle

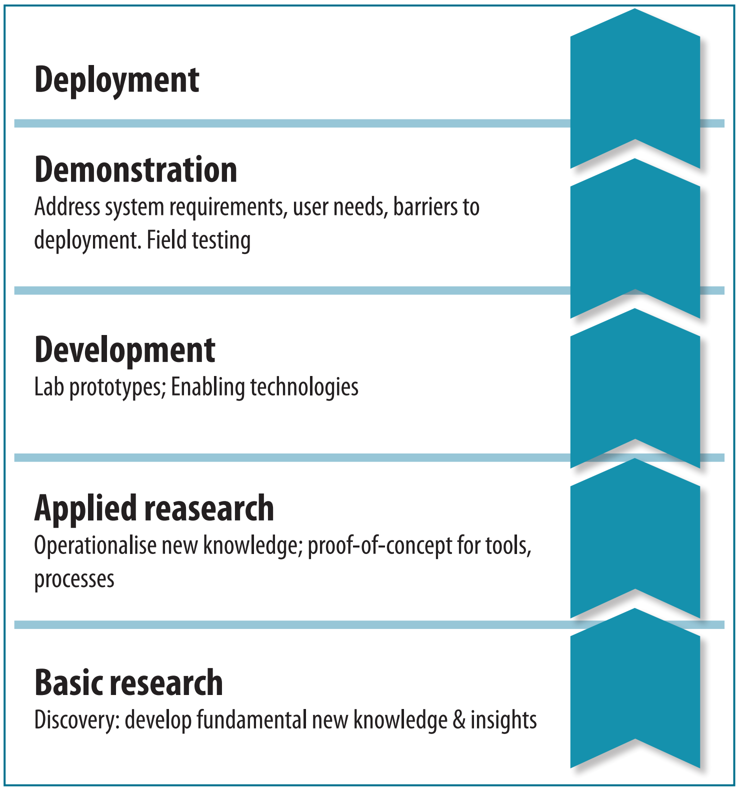

Figure A1.4: Schematic illustrating phases of 'research value chain'

Research and innovation activities are often categorized in terms such as 'basic', 'applied', 'development' and so on. For some, the essential industry challenge-directed nature of manufacturing research implies activities that are highly applied or developmental. For others, manufacturing research activities extend across the full 'research value chain' illustrated in Figure A1.4.

Indeed, many stakeholders emphasize the importance of effectively and efficiently translating new knowledge between these phases – from discovery, to operationalisation, to development of enabling technologies and processes, to system integration and ultimate deployment in real-world manufacturing systems.

Real innovation processes are, of course, highly non-linear. There are many feedback loops, as well as different levels of user engagement, required infrastructure, skill sets, and contributions from different research domains.

This translational nature of research – with its feedback loops, user engagement, project interactions and evolving infrastructure – is illustrated in Figure A1.5. This schematic is adapted from the strategy framework of the US National Science Foundation's Engineering Research Centers (ERC) programme. The ERCs are critical-mass university–industry research centres, many of which address manufacturing-related challenges. It is interesting to note that the ERC programme requires funded centres to address all research phases illustrated in Figure A1.5, and places particular importance on effective knowledge translation and integrated system demonstrator goals.

Some international manufacturing research leaders interviewed as part of this study suggested that activities relevant to manufacturing research were also siloed within and between government agencies – with insufficient interaction between organisational structures defined in terms of distinct research value chain phases ('basic' research, 'applied' research, technology development, deployment, etc). Several leaders advocated

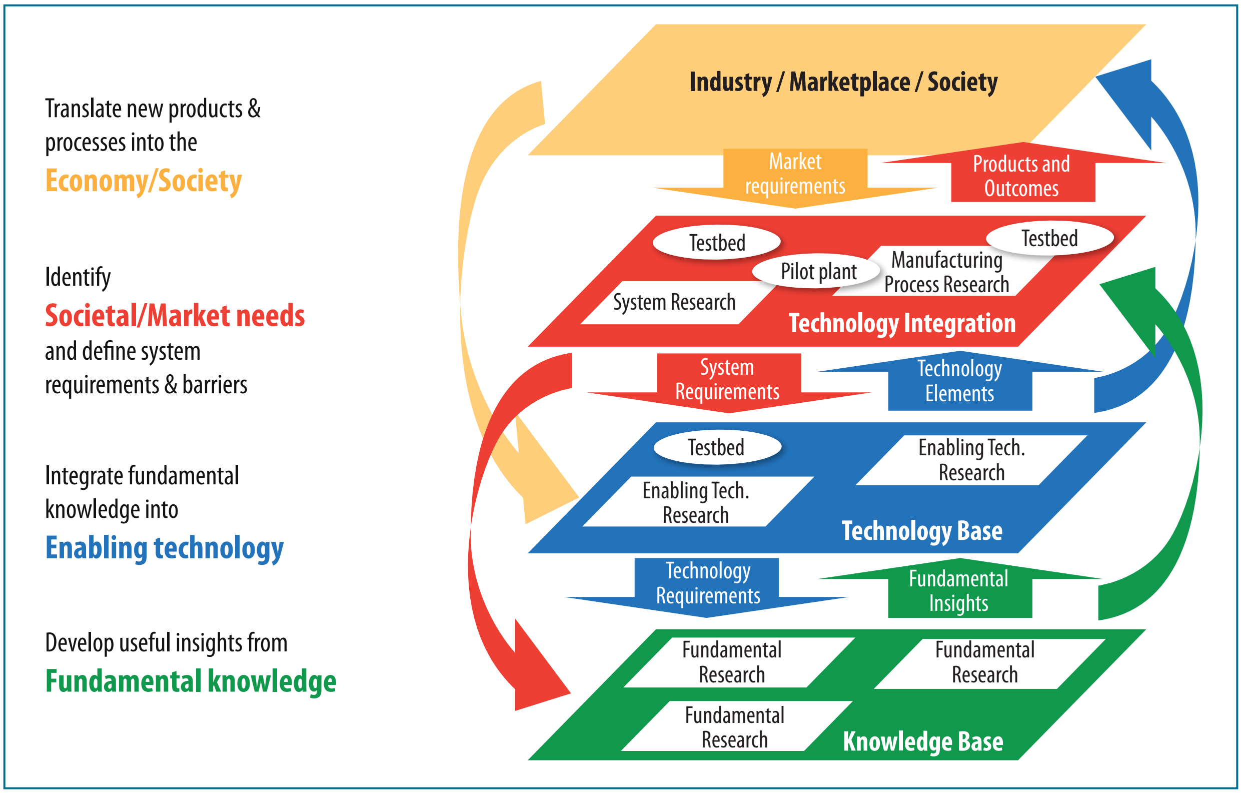

Figure A1.5: Schematic illustrating feedback and interactions between different phases of manufacturing research (Adapted from NSF Engineering Research Centers Strategy Framework)

more multi-agency approaches to support for science, engineering and technology development to enhance the effectiveness and efficiency of translating research findings from the research laboratory to the factory.

A1.8 International variations of 'manufacturing research'

Definitions of 'manufacturing research' also vary from country to country, where terminology tends to reflect the industrial strengths of each nation and/or the missions of different institutions within the national innovation system. Country variations of 'manufacturing research' are made yet more complex by national linguistic and idiomatic variations: For example, the dominant production-related research domains in the UK, Germany and Japan ('manufacturing research', 'production technology research', and 'monozukuri research') have significant variations in definition, emphasis and scope.

A1.9 Manufacturing research system-based framework

The scope of the Cambridge Institute for Manufacturing's study of international manufacturing research was relatively broad and inclusive. A range of research agencies, programmes, and activities designed to create new knowledge with potential to impact the productivity of manufacturing enterprises was explored. Particular attention was paid to those research activities and approaches that were primarily underpinned by engineering and the physical sciences.

In order to properly understand the nature of particular programmes, institutional

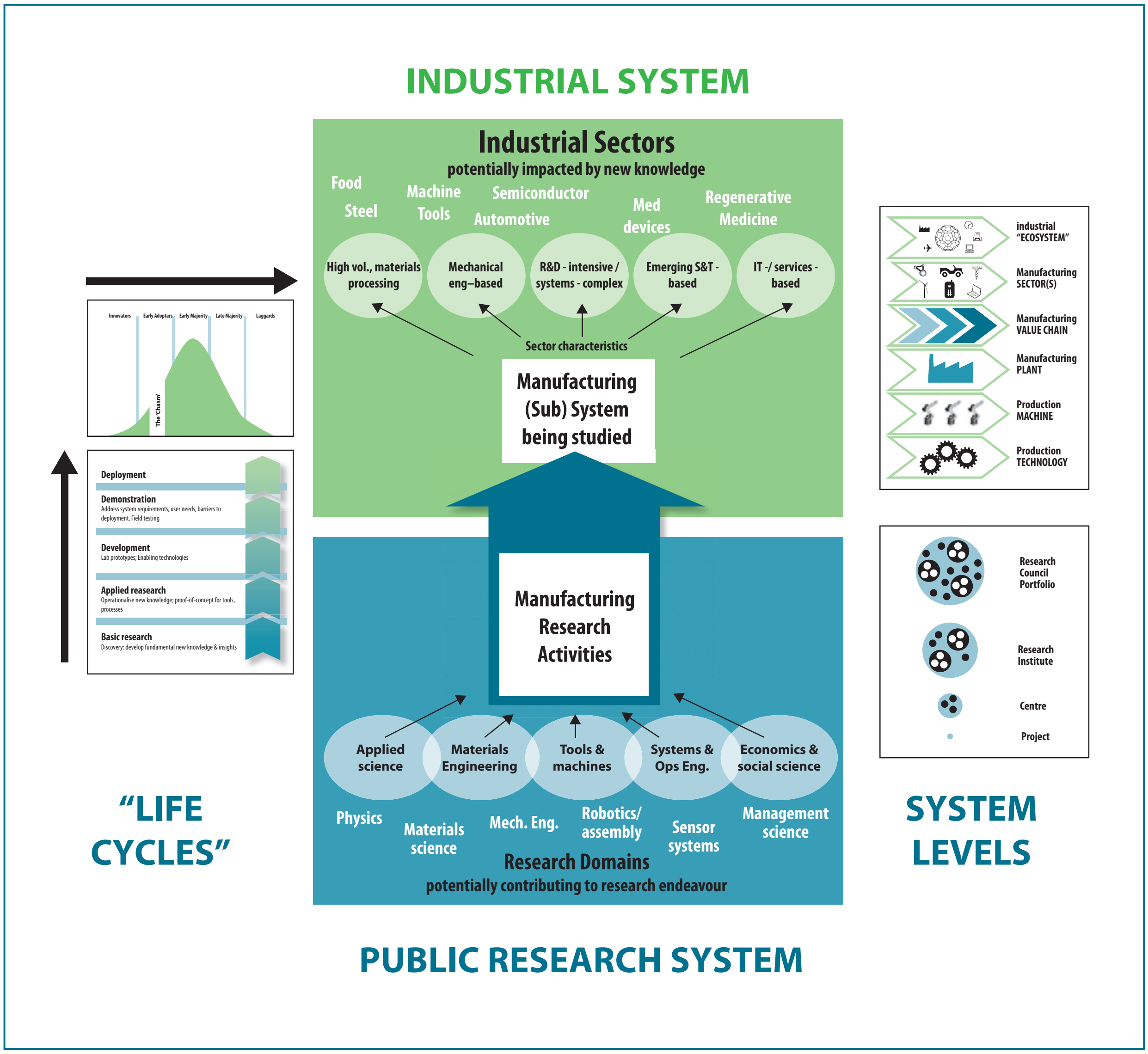

Figure A1.6: Schematic illustrating interactions between different dimensions of 'manufacturing research'

structures and research portfolios – and, in particular, to avoid any semantic confusion based on different definitions of 'manufacturing research' (as discussed above) – it proved useful to characterize activities in terms of:

- the manufacturing system being studied
- features of the industrial sectors potentially impacted
- life cycle stage and maturity of the systems and sectors being considered
- academic disciplines drawn upon to tackle the research challenges
- stage(s) in the research 'innovation chain' (from discovery to integration), including any key feedback loops and other collaborative interactions

The IfM project developed a novel conceptual framework (Figure A1.6) designed to accommodate a range of perspectives on manufacturing research, both from academic discipline-based and industrial systems perspectives. The framework was found to facilitate discussion and analysis of the translation of manufacturing research knowledge between different stages of the industrial value chain and the academic R&D 'value chain'. It also proved helpful in: clarifying stakeholder perspectives on 'manufacturing research'; analysing manufacturing research portfolios; understanding the dynamics of knowledge translation within manufacturing research; and gaining insights into models and effective practices for manufacturing R&D institutional configurations.

A1.10 Conclusion

Many of the most important emerging manufacturing research domains are intrinsically multidisciplinary, systems-based, and challenge-driven. The frontiers of new science and engineering knowledge with the potential to impact the productivity of manufacturing enterprises are constantly shifting. In this context, traditional concepts of 'manufacturing research' – reflecting established industrial sectors or academic disciplines – may no longer be adequate.

In particular, in an era of accelerating global competition, scientific discovery, technological innovation, and industrial system-complexity, it will be increasingly important to further characterize manufacturing research activities in terms of industrial and research 'life-cycles', the production system of analysis; and their broader industrial system context.

This more comprehensive characterization of manufacturing research may have potential to help industrialists, researchers and policy makers to articulate more clearly areas of critical need and future industrial challenges; and to apply new knowledge and future investments with greater precision and timeliness. It may also facilitate multi-agency approaches to supporting science, engineering and technology development that enhance the effectiveness and efficiency of translating research findings from the research laboratory to the factory, and to the customer.

Appendix 2: Sustainable manufacturing research

One of the most important and topical manufacturing research themes that emerged during the course of this review was 'sustainable manufacturing research'. Across all nations, there is growing interest in the potential of multidisciplinary research efforts to address challenges associated with the manufacture of products (and delivery to consumers) using materials and processes in way that minimizes environmental impact, and conserves energy and natural resources. In this appendix we explore some international approaches, initiatives, and priorities related to this important research domain.

A2.1 Introduction

In our exploration of international approaches to manufacturing research, environmental and resource sustainability was considered one of the most important drivers influencing the future of manufacturing; and 'sustainable manufacturing research' was probably the most commonly cited emerging research priority (or 'hot topic') across all economies.

Although there has been considerable research interest in themes related to resource-efficient and environment-friendly manufacturing for many years [e.g. Westkamper, 2000; Allen, 2001], there has been a significant increase in attention, investment and activity in the last couple of years. This importance and prioritisation is largely driven by societal pressure (related to the climate change and 'green' agendas) and consequent government regulation. The growing importance of the theme is reflected within a range of recent national manufacturing research strategy and foresight exercises in a number of countries [FhG ISI, 2009; Teknikföretagen,2009; Abele, 2010]. Sustainable manufacturing has been one of the most dominant themes across a broad range of manufacturing research conferences, as well as specially convened summits and symposia [NIST, 2009; CIRP, 2010; MIT, 2010; FhG, 2011]. Furthermore, some of the most high profile international manufacturing research initiatives and recently launched R&D centres have been in the area of sustainable, resource-efficient manufacturing, for example: the Sustainable Production Initiative (Chalmers and Lund, Sweden); the Sustainable Manufacturing Centre (SIMTech, Singapore).

Across most nations reviewed as part of this study, the term 'sustainable manufacturing research' was generally understood to refer to a range of research endeavours addressing challenges associated with the manufacturing and delivering of products to consumers using materials and processes in ways that minimize damaging environmental impacts, and conserve energy and natural resources in ways that are both safe for employees, communities, and consumers while remaining economically competitive. Although different nations have variations in emphasis and terminology related to sustainable manufacturing research themes – e.g. 'minimal manufacturing' and 'green monozukuri' (Japan), 'sustainable manufacturing' (USA), 'environmentally benign manufacturing'

(USA), 'resource-efficient production' (Germany), 'sustainable production' (Sweden), etc – there appears to be general agreement on the multidisciplinary, systems-nature of this 'grand challenge' research domain. In particular, there seems significant consensus that the scope of the sustainable manufacturing research agenda needs to extend beyond the production stage of the industrial value chain, across a product's entire lifetime (including its disposal phase) and encompass the whole system of integrated components, energy, and transportation required to assemble the final product and deliver it to customers. The customer use phase and end of life management aspects are also considered important in this domain. In addition to significant societal pressures to adopt increasingly resource-efficient and environmentally-friendly manufacturing practices, there is a growing sense that national manufacturing enterprises and sectors may gain potential competitive advantage from addressing the sustainability agenda throughout the entire product and production cycle, and manufacturing-consumption system.

In the following sections we briefly explore different approaches, initiatives, and priorities related to sustainable manufacturing research in a number of countries, notably the USA, Germany and Japan, but we also point to selected activities in other nations. The observations outlined below were made in the course of our broader exploration of international approaches to manufacturing research. We have not set out to conduct a comprehensive or systematic analysis of the sustainable manufacturing research domain. Consequently, while we hope we have highlighted some approaches and initiatives of interest, some important issues and activities may have been omitted.

A2.2 United States of America

Sustainable manufacturing and the manufacturability challenges of novel green technologies are an important part of the US policy discourse on advanced manufacturing (and priority research themes). In recent years there have also been a number of high profile workshops and summits addressing the challenges of sustainable manufacturing [e.g. NIST, 2011; MIT, 2010; NIST, 2009].

The importance of sustainable manufacturing is highlighted within the recent white papers on advanced manufacturing prepared for the President's Council of Advisors on Science and Technology [STPI, 2010]. These papers define sustainable manufacturing in terms of the manufacturing practices that use processes and materials in such a way as to minimize a product's environmental footprint. The goals of 'sustainable manufacturing', in this context, are considered to extend beyond simply minimizing energy usage and carbon emissions, to include the minimization of other resource usage (water, land, etc) and the reduction of material waste, effluents and toxins [STPI, 2010]. Consistent with other sustainable manufacturing policy documents, it is emphasized that sustainability goes beyond the production stage of manufacturing and 'extends to the product's lifetime use and the complex system of components, energy, and transportation required to both make the product and bring it to market'. There also seemed to be general agreement in the US that the sustainable manufacturing agenda requires a 'whole systems approach' to the application of sustainability principles at all stages of the product design and development process [NIST, 2009].

The US is home to many world-leading university-based sustainable manufacturing research activities (e.g. the Laboratory for Manufacturing and Sustainability, UC Berkeley and the Environmentally Benign Manufacturing group at MIT). Many of these sustainable manufacturing research activities are led out of university manufacturing or mechanical engineering departments, but many US academic experts highlighted the multi-disciplinary nature of the research domain and the need to engage research colleagues from a wide range of disciplines (such as materials science, engineering systems, or economics). Indeed, 'sustainable manufacturing' was regularly cited as an example of an evolving manufacturing research field where particular attention needed to be paid to ensure the emergence of this important research domain was not inhibited by journal, research grant, and tenure review processes prioritising metrics associated with more traditional engineering disciplines.

Sustainable manufacturing is an important theme across a number of Federal R&D agencies, including the National Science Foundation (NSF), the National Institute for Standards and Technology (NIST), and the Department of Energy (DoE), among others.

National Science Foundation

Although the National Science Foundation does not have a dedicated sustainable manufacturing-related research programme, the Foundation has a portfolio of sustainable manufacturing investments across a variety of programmes. A helpful recent summary of NSF investments related to sustainable manufacturing [Kramer, 2010] is captured in a presentation to MIT's 2010 'Manufacturing & Sustainability Summit' [MIT, 2010]. The main NSF division investing in sustainable manufacturing is Civil, Mechanical and Manufacturing Innovation, which makes sustainable manufacturing research-related investments through a range of funding mechanisms such as the Emerging Frontiers in Engineering and Grant Opportunities for Academic Liaison with Industry. Sustainable nanomanufacturing is one of the three thrust areas of the National Nanotechnology Initiative – a multi-agency initiative involving most of the US Federal R&D funding organisations. Several NSF-funded Nanoscale, Science and Engineering Centers address this agenda. The NSF's Engineering & Education for Sustainability (SEES) initiative specifically highlights the importance of manufacturing to the sustainability agenda.

The National Institute for Standards and Technology carries out a range of sustainable manufacturing-related activities. Information on these activities can be found on NIST's 'Sustainable Manufacturing Portal' website which usefully summarizes key programmes including: Sustainable and Lifecycle Information-based Manufacturing; Computing Carbon Weight (footprint) for Manufactured Products; Information Models for Sustainable Manufacturing; Standards and Testbeds for Sustainable Manufacturing; Survey and Analysis of Relevant Standards for Sustainable Manufacturing.

National Institute of Standards and Technology

NIST has also hosted important workshops related to sustainable manufacturing, including a 2009 event on 'Sustainable Manufacturing: Metrics, Standards, and Infrastructure' [NIST, 2010]. Although this event focused on 'measurement and standards' enablers' of sustainable manufacturing, it provides a useful introduction to many important approaches to sustainable manufacturing research in the United States. In particular, the report outlines some key government initiatives, together with industry perspectives, and insights from academic research community and NGOs. The event covered themes such as: the concept of sustainable manufacturing (indicators, metrics for sustainability, triple bottom line, etc); the design of sustainable products, services, and manufacturing systems; industry best practices for sustainable systems; next generation ICTs for sustainable manufacturing (e.g. ICT for design, supply chain optimization for sustainable manufacturing). The event also showcased a variety of sustainable technologies (and business models). Sustainable manufacturing research issues raised by the academic participants covered topics including: systems approaches to sustainable manufacturing research; manufacturing process analysis; sustainable design; supply chain analysis; metrics; reuse, recovery, and recycle; and information systems for sustainable manufacturing.

The NIST workshop led to a set of recommendations related to: infrastructure (e.g. software for gathering and sharing sustainability data, life-cycle assessment calculations); metrics (e.g. need for harmonization of existing metrics); standards (e.g. developing a strategy for the harmonization of standards and regulations); and best practices (e.g. related to new business models, eco-innovation, eco-labelling, reporting standards for suppliers, traceable life-cycle inventory data).

Department of Energy

The US Department of Energy's manufacturing research activities are described in more detail in Appendix 3. Because of the agency's mission, much of its manufacturing research portfolio is related to next generation manufacturing technologies and processes which are more energy (and resource) efficient. For example, the Industrial Technologies Program (ITP) of the DoE's office of Energy Efficiency and Renewable Energy not only provides technical assistance to manufacturing firms in support of energy-reduction best practices, but also makes research investments in the development of next generation manufacturing technologies and processes which are more resource efficient. One particular manufacturing-related ITP programme area addresses 'Energy-Intensive Industries' focused on R&D partnerships addressing resource efficiency challenges in (more traditional) manufacturing industries such as steel and chemicals.

A2.3 Germany

Sustainability and resource-efficient production are highlighted within the German 'High-Tech Strategy'. In addition to responding to social and environmental imperatives, interest in sustainable manufacturing research is driven by the potential to support the leadership position held by many German engineering firms in sustainable production technologies.

Resource- and energy-efficient production (and trends related to the market for raw materials and global climate change) has been a major theme at the Federal Ministry of Education and Research's bi-annual Karlsruhe Production Research Congress in both 2008 and 2010 [KAP, 2010]. The technological research institutes of the Fraunhofer-Gesellschaft have held a Congress on Resource-efficient Production in 2009 and 2011. Driven by the need to maintain Germany's manufacturing competitiveness through production using fewer raw materials and resources, the Fraunhofer Institutes came together to share expertise, concepts and research approaches related to the themes of resource-efficient production processes, energy-efficient production, and sustainable production concepts and factories [KRP, 2011].

Resource- and energy-efficient production is a research priority of the Federal Ministry for Education and Research (BMBF). This priority theme addresses research challenges associated with innovative energy- and material-efficient production across all stages of the manufacturing value chain and the entire product life cycle. BMBF identified priorities related to sustainable manufacturing systems and production technologies including: energy efficiency in manufacturing technology; energy efficiency in process engineering; energy-efficient machines, plants and components; targeted use of production technologies that optimise resource efficiency in the manufacture of a product (across product development and processing).

Resource-efficient production technologies were also identified in the Production Research 2020 exercise [Abele, 2011] commissioned by the BMBF. This study also highlighted manufacturing-related research challenges associated with production technologies for novel renewable energy technologies (and systems) and electric vehicles.

A separate analysis for the BMBF on 'Future Research Fields', carried out by the Fraunhofer Institutes for Systems and Innovation Research (ISI) and Industrial Engineering (IAO), highlighted the field of 'ProductionConsumption2.0' [FhG ISI, 2010]. This emerging research domain not only addresses resource-efficient industrial processes, but also social patterns of materials usage by consumers. The report suggests that this new domain will involve researchers from a wide range of disciplines, not only established manufacturing engineering domains such as production technologies research and materials engineering, but also services research, environmental research, and biotechnology; as well as contributions from the social sciences, innovation research and economics to help analyse co-evolution of processes within firms, technologies and society. Research efforts will focus on developing methods and concepts that will analyse materials flow patterns in production and consumption in a holistic and integrated way.

There are significant levels of sustainable manufacturing-related research carried out within German universities. The DFG's Funding Ranking for 2009 identifies the universities with the highest research incomes related to the Federal government's funding priority areas of 'cleaner environmental technologies and sustainable production'. These include RWTH Aachen, TU Freiberg, TU Dresden, TU Berlin and TU Munich.

The Fraunhofer Institutes also have considerable expertise and activities related to resource-efficient production (as evidenced in the FhG's recent Congress for Resource-Efficient Production). A range of manufacturing research-related Fraunhofer Institutes have significant expertise in this domain, including: Fraunhofer IWU (Machine Tools and Forming Technology), IFF (Factory Operation and Automation), IWB (Institute for Machine Tools and Industrial Management) and others.

Resource-efficient production technologies and systems are considered important areas of expertise for the next generation of German manufacturing engineering leaders. The Graduate School for advanced Manufacturing Engineering (GSaME) the University of Stuttgart, for example, includes sustainable manufacturing as one of its key research themes.

A2.4 Japan

Sustainable manufacturing is an important priority in Japan. The traditional Japanese concept of monozukuri (discussed in more detail in Chapter 7) involves endeavouring to make things as perfectly and efficiently as possible while respecting nature in terms of both the materials used and the environment. The twenty-first century monozukuri paradigm emphasizes reduction in resource consumption, less waste and minimal negative environmental impact from manufacturing industries.

Green Innovation is one of the key pillars of Japan's recently announced 4th Basic Science and Technology Plan. Sustainable manufacturing is an important aspect of Japan's eco-innovation policies and programmes, which include initiatives to support industries that use production technologies and systems which increase resource efficiency and recycle (as well as ones to support citizens engage in sustainable patterns of consumption). The technology roadmapping analyses issued by METI has identified a number of 'fusion technologies' including sustainable manufacturing as an important research priority.

Japan has particular sustainable manufacturing research strengths in key technical production areas such as design for environment techniques, simulation and modelling, and sustainable materials engineering [Evans, 2011]. Japanese researchers have proposed useful conceptual frameworks for research on sustainable product development and manufacturing [Waseda, Toyko and Osaka, 2007] and explored key trends in sustainable manufacturing [Nakano, 2010].

There appears to be significant agreement among Japanese sustainable manufacturing research experts on the importance of taking a whole-systems perspective to address sustainable manufacturing research challenges.

A variety of Japanese ministries, research agencies and institutes are engaged in advancing sustainable manufacturing. The New Energy and Industrial Technology Development Organization (NEDO) supports R&D for industrial, energy and environmental technologies. NEDO's dual mission is to enhance Japan's industrial competitiveness and address key energy and global environmental challenges. NEDO has funded research in a number of areas related to sustainable manufacturing, including 'eco-management of production system technology'. NEDO (together with its sponsoring ministry, METI) also plays a coordinating role by linking the private sector with the public sector, and promoting green R&D. The Japan Science and Technology Agency (JST) has a mission to facilitate innovation, including the advancement of S&T for sustainable development.

It is worth noting that, by contrast with the sustainable manufacturing agendas of the USA and Germany, which focus solely on their home economies, the policy discourse in Japan often includes a broader international agenda (including regional Asia Pacific and developing economies) [JST, 2010; Arimoto, 2011]. The role of developing economies as potential consumers of sustainable manufacturing technology was highlighted [JST, 2010), but there is also an acknowledgement of the important role they play in an interconnected economy and the need to consider these connections when evaluating issues at the level of the economy and the industrial system [IGES; Nakano, 2010].

A2.5 Sustainable manufacturing-related research in other nations

Many of the observations outlined above for the USA, Germany and Japan also apply to the other countries addressed in this report. In China, Singapore, Sweden (and many other countries) there is also growing interest in the potential of multidisciplinary research programmes, institutes and initiatives to address the sustainable manufacturing agenda:

- In **China**, a recently published report by the Chinese Academy of Sciences on 'Technological Revolution and China's Future-Innovation 2050' identifies key S&T-supported socio-economic systems for development, including a 'sustainable energy and resources system' and 'new materials and green manufacturing system' [CAS, 2010; CAS, 2011]. The report also identifies a range of strategic technology issues that are perceived to be critical to China's future innovation needs, including 'green manufacture of high quality elementary raw materials'. The CAS roadmapping process also generated a specific 'Advanced Manufacturing Technology' roadmap which highlights key trends relevant to future manufacturing research, including resource efficient production.

  The Chinese National Medium- and Long-Term Program for Science and Technology Development (2006–20) identifies a number of sustainable manufacturing-related priority topics, including: Green, automated process industry and corresponding equipment, recycling iron and steel process techniques and equipment; industrial energy efficiency; efficient development and utilization of mineral resources; etc [MOST, 2006].

- In **Sweden**, the Government's 2008 research and innovation bill 'A Boost to Research and Innovation' [Regeringen, 2008a] targeted research areas considered strategically important to Swedish society and industry. Strategic priority research areas identified in this bill were 'production science' and 'sustainable use of resources'. In 2009, the relevant R&D and innovation agencies (VINNOVA, Swedish Research Council, etc) assessed which universities and other higher education institutions were best suited to carry out the strategic initiatives. One of these flagship awards made under this programme was the 'Sustainable Production Initiative' led by Chalmers and Lund universities [SPI, 2010].

  The study "Swedish Production 2020" [Teknikforetagen, 2009a] identifies sustainable production as one of the critical challenges facing Swedish manufacturing. The report highlights the opportunity to achieve competitive advantage from methods and technologies to enhance resource efficient manufacturing; and from holistic understanding of environmental impact at all stages of the product realisation process, from idea to recycled product [Teknikforetagen, 2009].

- In **Singapore**, one of the most important new initiatives is SIMTech's 'Sustainable Manufacturing Centre' (SMC) which aims to develop methodologies and tools for assessment of sustainability in manufacturing, as well as R&D for sustainable manufacturing technologies, products and services. Furthermore, the new centre will provide Singapore's manufacturing industries with consultancy services and transferring of technologies for sustainability. The SMC will also support the development of human capital for sustainable manufacturing through 'Workforce Skills Qualifications', sustainable technology workshops and seminars [SIMTech, 2010].

  The Singapore Economic Development Board and the pharmaceutical company GlaxoSmithKline have recently launched the GSK-Singapore Partnership for Green and Sustainable Manufacturing [GSK-EDB, 2010]. This research initiative aims to enhance the manufacturing efficiency in pharmaceutical and fine chemical manufacture in Singapore. The partnership is designed to enhance the working relationship between Singapore-based firms, research institutes and universities through interdisciplinary research addressing sustainable manufacturing challenges showcased in the inaugural Green and Sustainable Manufacturing (GSM) Symposium, July 2011.

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Appendix 3: US agencies supporting manufacturing research

The United States is one of the world's leading manufacturing research nations. It is home to some of the most important global manufacturing corporations and many of the leading manufacturing and industrial engineering research universities. The US has a range of different mission agencies which support manufacturing-related research directly and indirectly. Key funders of manufacturing research include not only the National Science Foundation, but also the Department of Defense (DOD), the National Institute for Standards and Technology (NIST) and the Department of Energy (DOE). The extent of US manufacturing research (and the complexity of its manufacturing innovation system) can be underestimated if the activities of these agencies are not fully understood. In this appendix, we provide further background information on how these agencies engage in manufacturing-related research.

A3.1 National Science Foundation

The US National Science Foundation (NSF) is the federal agency whose activities are most analogous to the UK Research Councils. In particular, the manufacturing research activities of the NSF's Directorate for Engineering (ENG) are the closest in organization and agenda to those of the EPSRC.

A significant fraction of the NSF's manufacturing porfolio (and the majority of its manufacturing-related individual investigator awards) comes under the Division of Civil, Mechanical and Manufacturing Innovation (CMMI) – one of the four ENG research divisions. There are also, however, substantial investments in manufacturing-related research made by other divisions, notably the Engineering and Education Centres and the Industrial Innovation Partnerships divisions.

A3.1.1 Mechanical and manufacturing innovation

In addition to support for traditional engineering disciplines such as mechanical, industrial, manufacturing and materials engineering, CMMI gives significant encouragement to multidisciplinary research pursuing 'transformative' advances in real-world industrial systems and technologies, as well as technology platforms with the potential to impact a range of industrial systems and sectors.

CMMI's activities are organized into 'clusters' and associated sub-programmes (see figure A3.1) which give a good sense of the CMMI portfolio. In addition to the advanced manufacturing cluster, there are also manufacturing-related investments associated with systems engineering and design and mechanics and engineering materials. As well as activities associated with production of physical machines, equipment, etc, there are also investments addressing manufacturing challenges associated with emerging technologies (e.g. nanomanufacturing). There are also investments in 'softer' research associated with the non-physical production stages of manufacturing and manufacturing-related decision-systems engineering, e.g. manufacturing enterprise

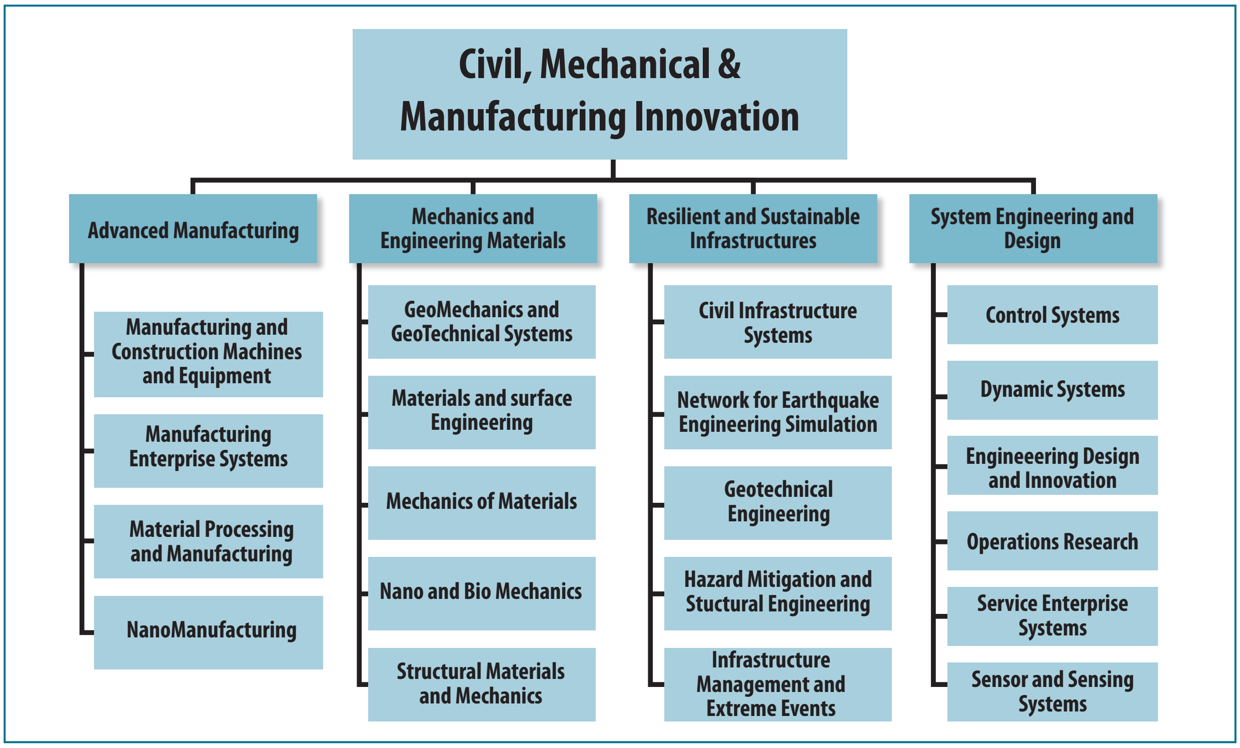

Figure A3.1: Organisational structure of the Division of Civil, Manufacturing and Manufacturing Innovation of the US National Science Foundation

systems; engineering design and innovation; operations research; and service enterprise systems.

A3.1.2 Critical mass research centres

A significant fraction of the ENG budget is invested in industry-facing critical mass research centres, notably the 'Engineering Research Centers' (ERCs) programme and the 'Industry/University Cooperative Research Centers' (I/UCRCs) programme. These programmes are discussed in more detail in Chapter 2.

The ERCs address engineering systems challenges that have the 'potential to spawn whole new industries or to radically transform the product lines, processing technologies, or service delivery methodologies of current industries'. Many of the current and 'graduated' ERCs have a strong focus on challenges of potentially significant impact on manufacturing industries. The I/UCRCs address large industrially-relevant problems, where the multidisciplinary research agenda and (often multi-sector) projects have been developed in close cooperation with industry partners. These different multidisciplinary challenge-driven centre models are discussed in more detail in the section on the US 'Manufacturing Industrial-Innovation Ecosystem'.

In addition to these university-industry centre programmes, the NSF's Division of Industrial Innovation and Partnerships leverages industrial support through programmes such as GOALI (Grant Opportunities for Academic Liaison with Industry) and the Partnerships for Innovation (PFI) program. A significant fraction of these activities address manufacturing-related challenges through university-based grantees working closely with industry to create enabling technologies, systems and processes for national needs.

A3.1.3 NSF education

The NSF also supports the National Center for Manufacturing Education – a source of materials, support services and professional development opportunities for educators and industry professionals. The As an NSF National Resource Center, NCME is 'a leader in manufacturing engineering technology education and offers a variety of products and services to both academic and industry professionals including: curriculum modules in nine subject areas covering technical skills, soft skills, math, and science; a self-guided curriculum development kit with a step-by-step instruction manual and template for creating competency-based activities; grant proposal development; grant management and evaluation; and professional development workshops in activity-based learning and authentic assessment. Most recently, the NCME has established the Manufacturing Education Resource Center (MERC) to serve as an electronic clearinghouse for high quality materials and best practices in manufacturing education'.

A3.1.4 NSF budget request The NSF's budget request for 2011, which reflected the Foundation's perceived priorities and strategy, highlighted 'transformative interdisciplinary research in areas of national interest' and stressed NSF's role in creating new knowledge that would contribute to the jobs and industries of the future. Domains receiving particular mention included the integration of nanotechnology and/or cyber-physical systems with traditional manufacturing industries (as discussed in the government's 'Framework for Revitalizing American Manufacturing').

NSF's strategy and evolving priorities are somewhat reflected in significantly increased budget requests in areas relevant to manufacturing, such the budget for the divisions of Civil, Mechanical & Manufacturing Innovation, Industrial Innovation & Partnerships, and Engineering Centres. The NSF's budget request related to the National Nanotechnology Initiative (NNI) increased in the key area of nanomanufacturing. Furthermore, the budget requests of some other directorates, such as Computer and Information Science (CISE), also addressed manufacturing-related research through, for example, proposed investments in their 'Cyber-Physical Systems' programme (addressing the cyberphysical manufacturing systems priority identified in the government's 'Framework for Revitalizing American Manufacturing' [EOP, 2009]) with the aim of developing insights, methods, and tools that will bridge the gap between approaches to the cyber and physical elements of cyber-physical systems design.

A3.2 Department of Defense

One of the most distinctive features of the manufacturing research ecosystem in the United States is the role of the Department of Defense (DOD). The critical role of the DOD in funding manufacturing research in the US was emphasized by the majority of stakeholders consulted as part of this study. Some of the most important DOD activities related to manufacturing R&D are carried out by DARPA (the Defense Advanced Research Projects Agency) and ManTech (the Manufacturing Technology Program).

DARPA invests significant sums in university-based research addressing production research challenges associated with military technologies and systems. Advances made in the production technologies and processes for these mission-critical defence systems often help overcome manufacturability challenges that would be considered too risky by private corporations and too advanced (in terms of technological readiness and demonstration) to attract support from civilian science foundations.

A3.2.1 DARPA

DARPA is a major funder of manufacturing research – its investments are often high risk, but new processes and technologies are taken to advanced levels of system readiness and deployability. R&D funding from agencies like DARPA allows university researchers to engage in real-world manufacturing problem-solving. The strategies (and sustainability) of many US manufacturing research centres are strongly influenced by research funding opportunities from the Department of Defense. DARPA provides an important revenue stream for university departments, but also university-affiliated intermediate research institutes such as Georgia Tech Research Institute, GTRI, or the (Boston-based) Fraunhofer Center for Manufacturing Innovation, CMI.

Although it is difficult to make direct comparisons between DOD investment in manufacturing R&D and investments by other federal agencies, the extent of DOD's contribution is reflected in analysis of its investment in US mechanical engineering research and from its investments in leading manufacturing research universities. In 2004, DOD accounted for 84% of federal agency investment in mechanical engineering. The dominance of DOD funding is significant for basic research, because other agency contributions have diminished. NSF in particular contributed significantly less in 2004 than in 1994 [NAP 2007]. DOD investment in important manufacturing research universities such as MIT is highly significant, accounting for 14% of overall university research income (compared with 9% for the National Science Foundation. It is noteworthy that DOD investment is being further concentrated in manufacturing-related departments, centres and laboratories [MIT, 2010].

In 2010, DARPA declared its ambition to invest $1B over five years to radically change US manufacturing by attempting to translate the successful model of the US semiconductor manufacturing industry –where product design companies outsource the production to 'foundries' – to other sectors. The goal would be to demonstrate the effectiveness of reconfiguring the vertically integrated manufacturing model that is dominant among many US manufacturers into more efficient manufacturing systems where 'foundries' distribute their costs across large numbers of different products, while the design-based companies use faster and more flexible facilities for their fabrication needs (e.g. prototypes, pilot manufacturing). In doing so DARPA will address a fundamental technical challenge associated with the translational process of manufacturing new things. The DARPA Director has characterized this challenge (which confronts all manufacturers) in terms of what happens at the 'seams' of manufacturing – difficulties that arise between each stage of the production process: between design and prototyping, early production runs, limited production levels, and – ultimately – large-scale manufacturing. It is issues at these 'seams' that are the source of unanticipated production delays and cost overruns.

As part of this initiative, in September 2010 DARPA launched 'Adaptive Vehicle Make' (AVM), a suite of programmes aimed at dramatically reducing production development timescales for defence systems by decoupling the design and production build phases of the manufacturing process.

> "To innovate we must make… Regina Dugan, DARPA Director

Other DARPA manufacturing programmes include, for example, the 'Disruptive Manufacturing Technologies' programme run by the Defense Science Offices focused on rapid, affordable manufacturing process development.

A3.2.2 ManTech

The other major manufacturing R&D programme of the DOD is the Manufacturing Technology Programme (MANTech). The goal of ManTech 'to provide cost savings, improve technology implementation with an early focus on manufacturing, reduce manufacturing lead time, provide faster surge capabilities, improve manufacturing processes for greater reliability, and rapidly respond to Warfighter requirements.'

The ManTech strategy extends beyond the more traditional focus on processing and production technologies to address emerging defence manufacturing needs associated with an increasingly global supply base and the capacity to respond flexibly and effectively to rapidly changing mission needs. In this way the DOD is confronting an extreme version of globalization and manufacturing timescale phenomena that also face civilian manufacturing enterprises.

A3.3 National Institute for Standards and Technology

The National Institute for Standards and Technology (NIST) has a range of activities related to manufacturing carried out through the Manufacturing Extension Partnership (somewhat analogous to the UK Manufacturing Advisory Service) and its Manufacturing Engineering Laboratory. NIST also runs the Technology Innovation Program – a high-risk, high-reward technology R&D funding programme addressing areas of critical national need – which has made significant investments in manufacturing-related research. NIST has also convened a number of national workshops on important manufacturing-related topics.

NIST hosts a 'Manufacturing Portal' website which usefully summarizes its activities across a range of manufacturing-related subject areas: Green Manufacturing; Lean Manufacturing; Metrology; Nanomanufacturing; Ontologies; Process Improvement; Product Data; Robotics; Simulation; Supply Chain; Sustainable Manufacturing; and Systems Integration.

A3.3.1 Technology Innovation Program (TIP)

The Technology Innovation Program funds firms and higher education institutions (and other organizations, e.g. national labs) to address high-risk, high-reward research challenges with the potential to accelerate innovation in areas of critical national need for the United States. These cost-shared research projects are typically led by firms, but research universities can also participate as contractors, or even lead a joint venture when partnered by one or more SMEs.

The Technology Innovation Program uses a 'white papers' process to solicit recommendations from key stakeholders (such as industry, academia, learned societies and government agencies) on research and innovation challenges associated with areas of critical national need. Over the last couple of years this process identified as priority challenges associated with the needs of US manufacturers to efficiently move novel materials emerging out of the research base into production and the market place. In particular, the consultation process indicated that competitiveness of process-based industries in the US could be significantly improved through technological innovations to critical manufacturing processes which would 'reduce costs, save time, increase quality or reduce waste'. The 2010 TIP competition focused on manufacturing technologies. The competition entitled 'Manufacturing and Biomanufacturing: Materials Advances and Critical Processes' was targeted at radical materials science and engineering advances which would lead to 'new products with advanced features and improved characteristics that will enter the market more quickly'. The 2009 TIP competition also included a manufacturing theme: 'Accelerating the Incorporation of Materials Advances into Manufacturing Processes'.

A3.3.2 Manufacturing Extension Partnership (MEP)

The Manufacturing Extension Partnership is a network of not-for-profit centres that offers SME manufacturers a range of support programmes and services related to the key areas of 'continuous improvement', 'technology acceleration', 'supplier development', 'sustainability' and 'workforce'. MEP helps translate research developed in US universities, national labs and corporations into the operations of SME manufacturers.

A3.3.3 The NIST Manufacturing Engineering Laboratory (MEL)

The Manufacturing Engineering Laboratory is involved in the development (and dissemination of) advanced technologies, guidelines, and services for US manufacturing firms. Its activities include: research investigating advanced engineering and manufacturing materials; development of novel manufacturing processes, technical data, and standards; studies of manufacturing enterprise integration. MEP also funds collaborative manufacturing research pilot grants and manufacturing fellowships. The Laboratory also carries out a broad range of research and analysis related to its mission to support US manufacturing, including advanced robotics and automation, sustainable manufacturing and energy efficiency, life cycle assessment and productivity measurement. MEL's activities support both traditional manufacturing industries (e.g. automotive, agricultural machinery) and emerging-technology-based industries (e.g. photonics, nanotechnology).

A3.3.4 Workshops, symposia, forums and summits

Several stakeholders commented that NIST provides a valuable convening function by hosting a number of high-level workshops on topics related to manufacturing. For example, at the beginning of 2011, NIST held the workshop 'Extreme Manufacturing – What are the technology needs for long-term US Manufacturing Competitiveness?'. This event was run in partnership with DARPA, NSF and NASA, and reflects some of the key manufacturing research-related questions and themes being discussed in the US. The workshop was also intended as an attempt to initiate a new forum for interagency initiative discussions. In particular, a key aim of the event was to identify crosscutting R&D investments needed to build the innovation infrastructure for successful US manufacturing enterprises. The participants also explored opportunities to develop a long-term vision for manufacturing. Other recent national workshops include 2009 events on 'Sustainable Manufacturing: Metrics, Standards, and Infrastructure Needs' and 'Challenges to Innovation in Advanced Manufacturing: Industry Drivers and R&D Needs'.

A3.4 Department of Energy

Historically, the US Department of Energy (DOE) has made significant research contributions to the development of a range of materials and electronics manufacturing innovations. A notable example is the research carried out by the National Laboratories at Sandia and Lawrence Livermore which led to the development of Extreme Ultraviolet Lithography for nanoscale integrated circuit production.

DOE National Labs continue to carry out some research activities associated with manufacturing challenges related to US energy needs. In fact, one of the questions being explored by the President's Council of Advisors on Science and Technology study of US advanced manufacturing is whether the mission of the national laboratories should be expanded to include 'R&D challenges relevant to a broad range of manufacturing industries'.

The DOE has a portfolio of overlapping R&D programmes that span the innovation spectrum from more fundamental scientific research through technology development, demonstration, and integration, all the way to support for the commercialization of new energy technologies. See Figure A3.2 [STPI].

<table>
<tr><th>Fundamental science</th><th>Applied science</th><th>Technology development</th><th>Technology integration & economic feasibility</th><th>Pilot projects</th><th>Deployment/ commercialisation</th></tr>
<tr><td colspan="2">Energy Frontier Research Centers (EFRC)</td><td colspan="4"></td></tr>
<tr><td colspan="4">Energy Innovation Hubs (EIH)</td><td></td><td></td></tr>
<tr><td></td><td colspan="4">Advanced Research Projects Agency – Energy (ARPA-E)</td><td></td></tr>
<tr><td colspan="2"></td><td colspan="4">Industrial Technologies Program (ITP)</td></tr>
<tr><td colspan="2"></td><td colspan="4">Building Technologies Program (BTP)</td></tr>
<tr><td colspan="4"></td><td colspan="2">Innovative Technology Loan Guarantee Program</td></tr>
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Figure A3.2: Schematic of DOE R&D programmes against the innovation chain [Source: DOE]

A number of these manufacturing-related programmes are described briefly below, in particular:

- Industrial Technologies Program (ITP)
- Energy Frontier Research Centers (EFRC)
- Advanced Research Projects Agency – Energy (ARPA-E)

A3.4.1 Industrial Technologies Program (ITP)

One of DOE's Office of Energy Efficiency and Renewable Energy's main programmes which includes investments in manufacturing-related research is the Industrial Technologies Program. In addition to providing technical assistance to manufacturing firms and sharing of energy-reduction best practices, ITP also invests in targeted R&D programmes associated with next generation manufacturing technologies and processes which are more resource efficient. ITP supports both R&D (including applied research, prototyping, demonstration activities) and also the commercialization of novel energy-efficient technologies.

The Industrial Technologies Program, for example, includes investments in cost-shared R&D for 'Cross-cutting Technologies' – technology platforms with the potential to impact a range of energy-intensive industries. Manufacturing-related cross-cutting technologies include 'industrial materials for the future', 'nanomanufacturing', and 'sensors and automation'. Another manufacturing-related ITP programme area addresses 'Energy-Intensive Industries'. This programme invests in R&D partnerships focused on traditional manufacturing industries including metal casting, steel, and chemicals.

A3.4.2 Energy Frontier Research Centers (EFRC)

EFRCs are integrated, multi-investigator centres which involve universities, national laboratories, firms and other organizations that carry out more fundamental research addressing energy-related 'grand challenges' and use-inspired 'basic research needs'. Although the EFRCs focus on more basic science and engineering research, a number of centres include within their research agendas manufacturability challenges of emerging technologies and processes, such as low cost manufacturability of organic solar cells and low power exciton-based electronic devices [EFRC, 2010].

A3.4.3 Advanced Research Projects Agency–Energy (ARPA-E)

ARPA-E is, as the name suggests, modelled on the Defense Advanced Research Projects Agency (discussed above). ARPA-E pursues high-risk, potentially high-return R&D challenges focused on potentially transformative energy technologies. Several ARPA-E projects address manufacturability challenges associated with novel emerging technologies in areas such as batteries research and biofuels.

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