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PART II

Chapter 11

The rise of advanced manufacturing institutes in the United States

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In the decade of the 2000s, US manufacturing employment fell by one-third, 64 000 factories closed, manufacturing capital investment and output suffered, and productivity growth dropped. The US had been systematically shifting production abroad, and studies suggested that the decline in its production capability was affecting its innovation capacity, which had long been viewed as the country's core economic strength. This chapter reviews the origins of the policy response to this dilemma, which came to be called "advanced manufacturing". The chapter traces the way the foundational concepts were developed in a series of reports; explores how a new innovation system response was developed to strengthen the production system; examines the key new policy mechanism, the manufacturing innovation institutes, which is a complex public-private collaborative model to develop new production technologies and processes, combined with workforce education; and, reviews how the new institutes are working, lessons learned as they have started up, and possible enhancements that could expand their policy reach. These new approaches – an advanced manufacturing programme – if implemented, could play a role in strengthening the US manufacturing sector. They could also play a role in moderating the serious social disruption created by the decline in manufacturing.

Introduction: American manufacturing in decline

In the decade of the 2000s, the manufacturing sector in the United States experienced significant disruption.1 The Great Recession of 2007-08 accelerated the changes but they were structural, not simply caused by the economic crisis. There was adversity in manufacturing jobs, capital investment, output, productivity and trade. One-third of the US manufacturing workforce lost their jobs in the course of the 2000s. This economic disruption led to social disruption (Bonvillian, 2016). While most Americans once assumed they were becoming one big middle class, instead, a working class facing declining incomes is now in clear, angry view. Manufacturing had long offered a path to the middle class for American high school-educated men. But from 1990-2013, the median income of men without high school diplomas fell by 20%, and of men with high school diplomas or some college education fell by 13% (Kearney, Hershbein and Jacome, 2015). In parallel, income inequality had significantly increased in the past decade and a half. The decline in manufacturing was not the only cause, but it was a significant one. Driven by these economic realities, a new manufacturing effort between federal and state governments, industry, and universities materialised in the wake of the Great Recession. It was an effort to bring systematic innovation back to US manufacturing and known as "advanced manufacturing". This chapter discusses how this policy emerged, its elements and, particularly, its centrepiece, a network of new advanced manufacturing institutes, which numbered 14 by the beginning of 2017.

The decade of the 2000s

The US manufacturing sector had a devastating decade over 2000-10 and has only partially recovered (Nager and Atkinson, 2015). The decline is illustrated by five measures: employment, investment, output, productivity growth assumptions and trade imbalance (Atkinson et al., 2012).

Employment. Over the past 50 years manufacturing's share of gross domestic product (GDP) shrank from 27% to 12%. For most of this period (1965-2000), manufacturing employment generally remained constant at 17 million; in the decade 2000-10 it fell precipitously by almost one-third (with 5.8 million jobs lost), to under 12 million, recovering by 2015 to only 12.3 million.2 All manufacturing sectors saw job losses over 2000-10,3 with sectors most prone to globalisation, led by textiles and furniture, suffering massive job losses.
Investment. Manufacturing-fixed capital investment (plant, equipment and information technology [IT]), if cost adjusted, actually declined in the 2000s (down 1.8%), the first decade this has occurred since data collection began.4 Investment declined in 15 of 19 industrial sectors (Stewart and Atkinson, 2013).
Output. Data shows US manufacturing output growth of only 0.5% per year over 2000-07 (before the Great Recession), and zero output growth per year over 2007-14, despite the gradual overall economic recovery following 2008 (Scott, 2015). This was lower than both GDP growth and population growth. In the Great Recession itself, manufacturing output

fell dramatically, by 10.3% over2007-09, followed by the slowest economic recovery in total GDP in 60 years (Atkinson et al., 2012).

Productivity. Recent analysis shows that the productivity growth rate in manufacturing averaged 4.1% per year during 1989-2000, when the sector was absorbing the gains of the IT revolution. However, over 2007-14 productivity growth in manufacturing fell to only 1.7% a year.5 Because productivity and output are tied, the decline and stagnation in output cited above helps explain the lower level of productivity increase in the later period. Compared to 19 other leading manufacturing nations, one major study found the United States was 10th in productivity growth in manufacturing and 17th in net output growth in the period 2000-10 (Atkinson et al., 2012). So, taken together, the evidence suggests that productivity gains were less than initially estimated, and so were not the significant cause of the one-third decline in manufacturing employment many thought (Scott, 2015; Atkinson et al., 2012). Political economist Suzanne Berger has noted that many economists thought manufacturing was like agriculture – a story of relentless productivity gains allowing an ever smaller workforce to create ever greater output. Berger found the analogy with agriculture to be simply incorrect in recent years because the assumed levels of productivity gains were in fact lower (Berger, 2014). This means one has to look at an overall decline in the sector itself to discover why manufacturing lost nearly one-third of its workforce in a decade.

Trade imbalance. In 2015 the United States ran a trade deficit (balance of payments in imports over exports) in manufactured goods of USD 832 billion.6 As of 2015, that total included a USD 92 billion deficit in advanced technology products, a deficit which keeps growing.7 The idea that the United States could keep moving up the scale to produce higher-value products – that it could lose commodity production and keep leading production of advanced technology goods (see e.g. Mann [2003]) – is undermined by this data. Gradual growth in the services trade surplus (USD 227 billion in 2015)8 is dwarfed by the size and continuing growth of the deficit in goods: the former will not offset the latter any time in the foreseeable future. So having a highly developed services economy does not allow the United States to dispense with a production economy.

To summarise, during 2000-10 US manufacturing employment fell, manufacturing capital investment fell, manufacturing output fell, manufacturing productivity was lower than previously assumed, and manufacturing trade was seriously imbalanced, with the strong US services sector offering only a limited offset. Overall, the US manufacturing sector has been hollowing out. The post- 2009 manufacturing recovery from recession has been the slowest in history: while there has been some manufacturing job and output recovery, these remain below pre-recession levels. The underlying structural problems in the sector still need addressing.

Trade effects

Paul Samuelson sounded an alert in a 2004 article attacking mainstream views of the net benefits of trade: he found such views “dead wrong about the assumed necessary surplus of winnings over losings.” Instead “the new labour-market clearing real wage has been lowered” by a realistic view of trade dynamics, creating "new net harmful US terms of trade." (Samuelson, 2004). Autor, Dorn and Hanson (2016) have substantiated a picture of problematic trade effects (see also Preeg [2016], Meckstroth [2014] and Dahlman [2012]). They found that the trade relationship between the United States and the People's Republic of China (hereafter "China"), formed in the 1990s and formally recognised in the 2001 WTO agreement, affected many labour-intensive industries in the United States, where significant

numbers of those jobs shifted to China. This shift came at a heavy cost to US workers when many blue-collar jobs in particular disappeared, with the communities where they worked also suffering economically. Autor, Dorn and Hanson (2016) also show that the adverse consequences of trade can be enduring, with the United States as yet unable to get past the shock of the loss of millions of jobs in numerous communities.[9]

As economics Nobelist Michael Spence has noted, "Globalization hurts some subgroups within some countries, including the advanced economies... The result is growing disparities in income and employment across the US economy, with highly educated workers enjoying more opportunities and workers with less education facing declining employment prospects and stagnant incomes." (Spence, 2011). Just as manufacturing employment was a key to enabling less educated workers to enter the middle class after World War II, the loss of manufacturing jobs has been a key element in the decline in real income for a significant part of the American middle class in recent decades. Obviously, the 2008-09 Great Recession, when manufacturing was a leading victim, played a role, but it appears that there is no getting around the effects of trade, which have been longer term.

The innovation perspective

If the picture on the US production side is problematic, what of innovation? The United States retains what is probably still the world's strongest early-stage innovation system, although competition in this area from other countries is growing. Any manufacturing strategy must seek to use this comparative innovation advantage. However, in the past, research and development (R&D) in the United States has had only a very limited focus on the advanced technologies and processes needed for production leadership. This is in sharp contrast to the approach to manufacturing R&D taken by Germany, Japan, Korea, Taiwan and now China, which have "manufacturing-led" innovation (Bonvillian and Weiss, 2015). As discussed in more detail below, the United States – its government agencies and other organisations – had simply not applied the innovation system to what turns out to be a crucial stage in innovation – production, particularly initial production – using complex, high-value technologies. This stage involves highly creative engineering and design, and often entails rethinking the underlying science and invention: production is part of the innovation process and not severed from it. Missing this link between production and innovation created a major gap in the US innovation system.

The reach of manufacturing into the American economy

Manufacturing remains a major sector of the US economy: it represents approximately 12.1% of US GDP, contributing USD 2.09 trillion to a USD 17.3 trillion economy and employing 12.3 million in a total employed workforce of some 150 million.10 On average, manufacturingworkers are paid at least 20% more than workers in services and non-manufacturing (Helper, Kruger and Wial, 2012). Manufacturing firms employ some 64% of US scientists and engineers, and these firms perform 70% of industrial R&D (Tassey, 2010, citing Bureau of Economic Analysis [BEA] and National Science Foundation [NSF] data). Thus US manufacturing strength and the strength of its innovation system are directly linked.

Meckstroth (2016) develops new data that tell a story of the importance of manufacturing as part of the complex value chain of US companies. This study found that the manufactured goods value chain plus manufacturing for other industries' supply chains accounts for about one-third of GDP and employment in the United States. It further found that the domestic manufacturing value-added multiplier is 3.6, which is much higher than

conventional calculations. In other words, for every dollar of domestic manufacturing valueadded destined for manufactured goods for final demand, another USD 3.60 of value-added is generated elsewhere in the economy. Finally, for each full-time job in manufacturing dedicated to producing value for final demand, there are 3.4 full-time equivalent jobs created in non-manufacturing industries: this job multiplier is far higher than in any other sector. Higher value-added production industries appear to have even higher multipliers. To summarise, Meckstroth's central finding is that the current estimates of manufacturing's share of GDP are partial and seriously understated. Given its reach into the US economy, new policy perspectives on manufacturing decline appear to be necessary.

Advanced manufacturing emerges as a policy priority at the federal level

As Barack Obama was sworn in as president in January 2008 he faced the Great Recession, the first economic slowdown since the 1930s to approach Depression levels of economic decline, the highest long-term unemployment rate since the Depression and over 15 million unemployed (Bureau of Labor Statistics, 2012). As described above, manufacturing, along with construction, was the most heavily impacted sector. In 2008-09, the administration focused on getting Congress to pass, and then implementing, an economic stimulus bill, focused on short-term, "shovel-ready" job creation, and salvaging a bankrupt auto sector. With the stimulus in place, it began to focus on some of the underlying structural problems in the economy: manufacturing policy was high on that list.

The historical precedents for a federal manufacturing role

The federal role in the US innovation system largely stems from the Second World War, where it embarked on a series of major wartime technology efforts working in close concert with industry, industry laboratories and university researchers.11 At the end of the war this system was dismantled, but President Roosevelt's science czar, Vannevar Bush, worked with him to retain a key element that had emerged at scale during the war: federally-funded research universities supported by research agencies at the federal level. The problem at the end of the war was not the US manufacturing system: this mass-production-based system dominated world production. Instead, the challenge was creating a foundational research base building on what had begun during the war. So when the United States built a federallysupported innovation system, it was organised around early-stage R&D. Innovation in production was not even considered. As noted above, when Germany and Japan entered the post-war period, they had a different problem, rebuilding their industrial bases, so they focused on manufacturing-led innovation while the United States focused on R&D-led innovation.

Because production of new technologies is an important part of innovation systems, there was a major gap lurking in the US system, as suggested above. The US ran into trouble from this gap during its competition in the 1970s and 1980s with Japanese manufacturing. Japan had innovated in production technologies and processes to create quality manufacturing, capturing large parts of the auto and consumer electronics sectors. The US, content with its mass production model, had entirely missed this advance, and had to scramble for years to catch up.

As part of its catch-up to Japan's advances in production, it created a series of new programmes in the 1980s to supplement its basic research emphasis (Bonvillian, 2014):

- The **Bayh-Dole Act** was passed in 1980, and was the first of the new generation of competitiveness legislation. Historically, the federal government held the rights to the

results of federally-funded research. Since the federal government did not undertake technology implementation, this intellectual property sat on the shelf. The act shifted ownership of federally-funded research results to the universities where the research had been performed, giving universities a stake in its commercialisation, and spurring an entrepreneurship role for university researchers.
- The **Manufacturing Extension Partnership (MEP)** was authorised in1988, based on the success of the longstanding US agriculture extension programme. It aimed to bring the latest manufacturing technologies and processes to small manufacturers around the nation, since small firms were increasingly dominating US manufacturing, advising them on the latest manufacturing advances to foster productivity gains. MEP formed extension centres in every state, which states cost-shared, backed up by a small commerce department headquarters staff charged with programme evaluations and transmission of best practices to the centres.
- The **Small Business Innovation Research (SBIR)** programme offered competitive R&D grant funding to small and start-up companies, administered by the 11 largest federal R&D agencies as part of their research programmes. These grants aimed to ensure that small,

high-tech, innovative businesses were a part of the federal government's R&D efforts.

- The **Advanced Technology Programme** (**ATP**) was formed in 1988 in the Department of Commerce's National Institute of Standards and Technology (NIST) programme to fund a broad base of high-risk, high-reward R&D undertaken by industry. While it had success nurturing later stage development projects for new technologies, Congress gradually defunded the programme in the 2000s, viewing it as overly-interventionist federal "industrial policy."12
- **Sematech** was formed by a consortium of semiconductor fabricators and equipment makers that by the late 1980s was facing imminent demise from strong competitors in Japan. Because semiconductor technology was key to many defence systems the effort had national security implications, so industry funding was matched by the Defense Advanced Research Projects Agency (DARPA). The consortium focused on major efficiency and quality improvements in semiconductor manufacturing. After five years production leadership was restored and DARPA funding ended in 1996. Sematech continued as a key technology planning organisation to keep the industry on a Moore's Law roadmap. The Sematech model is the closest to the organisational approaches that came to be considered in the 2010-12 period.

But these manufacturing-related programmes remained modest and of limited scale because by the early 1990s the United States, relying on advances from its strong R&Doriented innovation system, was able to lead the launch of the IT revolution. The United States entered a decade of strong GDP and productivity growth, and largely forgot about manufacturing. Emerging manufacturing competition from China, exacerbated by the Great Recession, forced another wake-up call.

White House 2011 advanced manufacturing report

Against a backdrop of economic crisis and a series of new studies,13 a small group in the White House Office of Science and Technology Policy (OSTP) had been developing a report urging a strong new commitment by the administration to manufacturing, as a longer-term more structural approach than short-term economic stimulus.

The final 2011 OSTP report, entitled "Ensuring American Leadership in Advanced Manufacturing", defined advanced manufacturing as the manufacture of conventional or novel products through processes that depend on the co-ordination of information, automation, computation, software, sensing, and networking, and/or which make use of cutting-edge materials and emerging scientific capabilities (PCAST, 2011). The report argued that federal investments in advanced manufacturing could enable the United States to regain its status as a global leader in manufacturing, which would yield high-paying jobs, support domestic innovation, and enhance national security. However, the failure to lead in production would potentially jeopardise the nation's ability to develop the next generation of advanced products. Retention of manufacturing would enable new synergies, whereby design, engineering, scale-up, and production processes would provide feedback for product conception and innovation, helping to generate both new technologies and new latergeneration products.

The report proposed “shared facilities and infrastructure” where small and mediumsized manufacturing firms could develop new production approaches embodying productivity gains, allowing these firms to more rapidly prototype, test and make new products. The report recommended federal applied research support of advanced manufacturing processes that cut across a range of production sectors to enable producers to more rapidly develop new US-made sectors. This included, interestingly, “Supporting the creation and dissemination of powerful design methodologies that dramatically expand the ability of entrepreneurs to design products and processes.” (PCAST, 2011, p. iii).

The 2011 OSTP report further recommended developing partnerships between industry, universities and government, with government and industry co-investments, which could help develop emerging technologies. Included in the recommendations was a proposed “advanced manufacturing initiative” across government agencies that could link to industry-university collaborations to develop more detailed approaches. Importantly, issuance of the report, and the simultaneous announcement of a new public-private partnership to pursue this initiative, locked in a White House commitment to a manufacturing innovation strategy.

The Advanced Manufacturing Partnership begins: June 2011

The president announced, on 24 June 2011, an “Advanced Manufacturing Partnership” (AMP) and named Dow Chemical’s chief executive officer (CEO) and Massachusetts Institute of Technology’s (MIT) president as co-chairs of this industry-university-government consortium.

On the industry side, the AMP included CEOs from a diverse group of major companies, spread across industrial sectors. On the university side, the AMP included presidents of five universities with strengths in engineering and applied science.[14] On the government side, the chair of the National Economic Council (NEC) and the acting commerce secretary co-led a cross-agency effort. Within the White House, NEC and OSTP staff provided leadership. The agencies deeply involved in supporting the effort were the NIST in the Commerce Department, the NSF through its Engineering Division, the Department of Energy (US DoE) through its Energy Efficiency and Renewable Energy office (EERE), and the Department of Defense (US DoD) (through its Mantech programme). The President’s Council of Advisors on Science and Technology (PCAST), based in OSTP, provided an administrative home for the effort and formally issued the AMP report (although it was written by the AMP team).

AMP1.0 July 2012 report: "Capturing Domestic Competitive Advantage in Advanced Manufacturing"

The first AMP report called for an "advanced manufacturing strategy" based on a "systematic process to identify and prioritise critical cross-cutting technologies" (PCAST, 2012). That process should lead to an ongoing strategy, which in turn could be translated into more detailed technology roadmaps for each of the new technology paradigms. The report also developed a framework for prioritising federal investments in such technologies based on such factors as national need, global demand, US manufacturing competitiveness in the field and technology readiness. It also called for an assessment of the willingness of industry, university research and government to commit to the technology, such as whether, in the case of government, the technology could meet its national security needs (PCAST, 2012). Polling groups of manufacturers and university experts, the report developed a preliminary priority list of technology areas to be pursued: advancing sensing, measurement, and process control; advanced materials design, synthesis, and processing; visualisation, informatics, and digital manufacturing technologies; sustainable manufacturing; nanomanufacturing, flexible electronics manufacturing; biomanufacturing and bioinformatics; additive manufacturing; advanced manufacturing and testing equipment; industrial robotics; and advanced forming and joining technologies. Again, strategies for these technology areas were to be developed over time into true technology roadmaps that were to be co-ordinated across technologies and periodically updated.

To nurture these technologies, this first AMP report called for building R&D efforts around them. Significantly, it also called for the creation of manufacturing innovation institutes (MIIs), comprised of small and medium-sized firms linked to larger firms, backed by multidisciplinary university applied science and engineering, with cost-shared funding support from both government (federal and state) and participating industry. The idea was a translation into a US context of the successful German Fraunhofer Institutes, 60 of which were spread across Germany, in a wide range of technology focus areas. The US version was to be an industry-led model, shared and cost-shared, like the Fraunhofer Institutes, across small and medium-sized firms, with a supporting university technology development role in applied science and engineering, and with support from both national and state government. The US institutes were to operate at the regional level to take advantage of area specific industrial clusters, but be able to translate their technology and process learning to manufacturers at a national scale. To facilitate this national translation and to tie together the MIIs around jointly learned lessons, the report proposed a National Network of Manufacturing Innovation Institutes (NNMI). These policies were guided by a vision that there was a gap between R&D supported by government and the product development role of industry. A support system for the stages of technology development, technology demonstration and system/subsystem development – technology readiness levels (TRL) 4-715 – was simply missing. The network's role was to fill that gap.

The MIT study: “Production in the Innovation Economy” (PIE) – 2010-13

The MIT study PIE was published in 2013, after the AMP 2012 study. While there had been a number of major manufacturing studies in this period, MIT’s two-volume report, under development starting in 2010, was perhaps the broadest and most far-reaching, and its research findings significantly influenced the AMP reports.

At heart, the PIE study asked one major question: what production capabilities are needed to support innovation and to realise its benefits in high-quality jobs, strong firms,

business creation and sustainable economic growth? (Berger, 2014).16 Assuming what economists had long accepted, that innovation is required for economic growth and productivity, the PIE study examined “what it takes to sustain innovation over time and what it takes to bring innovation into the economy.” (Berger, 2014, Chapter 7). The PIE process reviewed innovation in products, in processes, in types of firms, in other nations, through technology advances and workforce improvements. The focus that the PIE study helped create in the United States, starting in 2010, was on the application of innovation theory to production. While such theory had been applied many times to particular new technologies, such as in IT, innovation theory had not been systematically applied to the US production system. It was a new look. The five overall areas the PIE study examined in turn led to a series of new policy approaches for each.

The PIE report found a globalised world economy in which research, development, production and distribution had become fragmented and dispersed. Enabling this was a shift in corporate ownership and control, where major, vertically-integrated corporations began to divest many of their attributes, from R&D to production to post-sales services. Few fully vertically-integrated firms remained. They had been reorganised under pressure from a financial services sector that, beginning in the 1980s, required firms seeking capital to reorganise around “core competency”, with leaner, “asset light” firms receiving higher stock valuations by the weeding out of their less profitable divisions (Berger, 2014). One of the first functions at many firms to go outside corporate boundaries was manufacturing, which reduced capital obligations and “headcount” commitments. Manufacturing units often shifted abroad. IT advances helped enable this development: computer-driven equipment using digital specifications allowed firms to produce goods without the vertical linkages previously required. The reduction of trade barriers worldwide and China’s entry into the World Trade Organization were further enablers of distributed production.

The shift to core competencies in firms, plus competition from abroad, thinned out the manufacturing ecosystem. Support for training systems, inducements for suppliers to adopt best practices, and the depth of supply chains all declined. While major firms had once supported strong industrial laboratories that undertook basic and applied research, basic research at the industrial level dropped, and applied work became much more focused on incremental development that could translate to the bottom line. Expansion was more frequently accomplished through mergers and acquisitions, not through inhouse innovation. Previously, large, vertically organised firms had created numerous "public goods", e.g. in research, training, and the transfer of technology and expertise to suppliers, that populated the ecosystem with spillovers that helped small and mediumsized firms. But private production of such public goods now declined.

To summarise, larger firms dropped their vertical model, focused on "core competency," went "asset light," and distributed their production. The resulting gaps in the ecosystem could be characterised as market failures because the declining network of complementary capabilities made firms less capable as they found it harder to access the former industrial commons. Small and medium-sized firms were increasingly what the PIE study termed "home alone", operating in a thinned-out industrial ecosystem. The end of local banking also hit small and medium-sized firms. As financial services pursued national and international investment models, the home town banker with personal knowledge of those he or she was lending to was disappearing. Capital became harder to find, so small and medium-sized firms had more difficulty in obtaining the resources to scale up their production of

innovations. In other words, the industrial ocean that the Main Street manufacturer used to swim in began to dry up.

The PIE study also told a technology story. A major example was studied in depth to evaluate the possible implications of innovation for production. This was a case study on a mix of challenging technologies to enable "mass customisation" (Berger, 2014). This entailed small-scale, local production using 3D printing and computer-driven standards with equipment that could make small lots of uniquely-designed products as cost efficiently as uniform mass production. The case study elaborated on the technologies to enable this and found the model possible. It would mark a dramatic turn in the nature of production. This "advanced manufacturing" innovation model for production was found promising, creating an organising principal for restoring the manufacturing ecosystem.

The study also told a story of problems in obtaining financing for "hard" technology startups as they scaled up for manufacturing: the venture capital system simply did not fit these firms, which required longer term and higher capital support than venture capital companies were attuned to (Reynolds, Semel and Lawrence, 2014).

Finally, the PIE study examined workforce needs. Earlier reports tended to query senior management in manufacturing, who unfailingly complained that they were not able to find skilled workers.[17] But if this sector had shed almost one-third of its workers in the decade of the 2000s, was there really a shortage? The PIE study questioned firms' hiring officials not about the availability of skilled workers but more pointedly about how long it took to fill jobs.

The answer was that open positions were being promptly filled in 76% of cases (Osterman and Weaver, 2014). There was no skills emergency. But 24% of manufacturing establishments still reported some level of long-term vacancies. This is where the story became more interesting. A subset in this group tended to include newer firms, working on more advanced technologies. These firms did face skill constraints. So if PIE was proposing the adoption of advanced manufacturing driven by new technologies and processes, it was clear that the training system would need to adapt to meet this challenge. The recommendations called for "a new skill production system" requiring employers to engage with community colleges, supporting government programmes at the federal, state and regional levels, and supporting intermediary organisations to help manage the linkages and communications.Overall, the PIE study called for rebuilding a thinned-out industrial ecosystem. New shared facilities and capabilities across firms and industrial sectors were required to bring more innovation into production. Larger firms and government could perform a convening function, comparable to what Sematech had achieved in semiconductor production in the late 1980s and 1990s. It found that a similar collaboration across firms, education institutions and public intermediaries could also work in the skills training context.

AMP2.0 October 2014 report: "Accelerating US Advanced Manufacturing"

The president "rechartered" the AMP in September 2013 to work on implementation of the 2012 report and to identify new strategies building on the earlier AMP1.0 report. This project marked the next major step in advanced manufacturing policy development.

Since the administration was in the process of creating manufacturing institutes, the AMP2.0 report focused on complementary policies (PCAST, 2014). In the area of technology policy, this report called for a national strategy co-ordinated across public and private sectors for "emerging manufacturing technologies". This strategy would include "prioritised manufacturing technology areas" which should be used to guide a "portfolio" of federal

"advanced manufacturing technology investments." To show that this concept could work, the AMP2.0 group surveyed priority emerging manufacturing technologies and developed their own pilot strategies in three technology areas identified by the study as priorities: advanced sensing, control and platforms for manufacturing; visualisation, informatics and digital manufacturing; and advanced materials manufacturing. The administration subsequently worked to create manufacturing institutes to cover these identified priority areas, drawing on the strategies.

Federal investment was not solely to focus on manufacturing institutes. The establishment of R&D support for manufacturing technologies was needed, and additional institutional entities were called for. These mechanisms included manufacturing centres of excellence, as well as technology testbeds which could act as additional infrastructure backing up the institutes. The R&D and support infrastructure were to be developed co-operatively with industry. An advanced manufacturing advisory consortium was called for to provide private sector input on both the strategy and the R&D infrastructure. The report foresaw that to thrive over time the manufacturing institutes had to be connected to a robust R&D effort and infrastructure in order to foster ongoing advances in the technologies the institutes were supporting. In addition, a "shared NNMI" was called for to network the manufacturing institutes so that ideas, technologies and best practices could be shared across institutes. Shared processes and standards to spread implementation of new manufacturing technologies were also recommended.

In the area of workforce training and development the report recommended a national system of portable, stackable manufacturing skill certifications. These would be used by employers in hiring and promotion, and would help production workers obtain readily transferable and recognisable skills. The development of online training and accreditation programmes with federal support through job training programmes was also proposed. AMP2.0 members themselves developed extensive manufacturing training toolkits and playbooks, as well as a pilot apprenticeship training programme

The report also had a work group on "scale-up policy" examining the difficulties faced by small and medium-sized firms and start-ups in obtaining financing for scaling up production of new innovations. This problem had been identified in the MIT PIE study, and extensive discussions were held with venture capital, corporate venture and private equity firms, as well as other possible sources of growth financing. An ambitious public-private scale-up investment fund was envisioned to finance pilot production sites for new technologies. In addition, a better system for linking manufacturers with potential strategic partners who could aid in the scaling up of production was called for. The scale-up gap became one of the key focus areas of the report. Although the administration subsequently proposed new scale-up financing, in a period of limited resources, Congress did not respond.

Congressional manufacturing legislation: 2014

The final saga in this summary of the major reports and efforts behind advanced manufacturing concerns Congressional legislation. For government action to be enduring, it must be authorised by Congress, and a foundation of regular and relatively stable appropriations must follow. As can be seen, government commitments ultimately flow from law and the corresponding funding, not administrative fiat.

Particularly after 2010, Congress was afflicted with deep ideological divisions, including within the majority Congressional party, and a corresponding inability to move legislation.

Despite this divide, Congress was able to pass significant manufacturing legislation on a highly bipartisan basis. This speaks to the political power of manufacturing, through the employment and relatively high wages it still commands, in American politics. After passing the House, and moving through Committee in the Senate, the manufacturing bill was added to a large annual omnibus appropriations bill to fund all the government agencies for the fiscal year. This was a "must pass" bill. As a "minibus" attached to the omnibus, it passed the House on 11 December and the Senate on 13 December 2014.

The legislation18 authorised the establishment of a network of 15 regional manufacturing institutes across the country, each focused on a unique technology, material or process relevant to advanced manufacturing (House Committee on Science, Space and Technology, 2014) which was to form a Network for Manufacturing Innovation. NIST was to be the lead agency in forming the network, but could collaborate with other federal agencies in selecting and awarding funding institutes, which must be cost-shared by industry and state or local governments. NIST was required to develop and periodically update a strategic plan for the network of institutes. It was also required to link the institutes to the existing MEP that offered efficiency and technology advice to small manufacturers in every state, and required institutes to take on education and training roles.

Of course, in the meantime a series of manufacturing institutes had already been established, sponsored by the by the US DoD's Mantech programme and the US DoE's EERE office. The bill's idea of having NIST leadership for new institutes did not match the reality of what was already evolving. But the bill amounted to an important Congressional validation of the manufacturing institute model. The bill also called for the creation of a network to connect the institutes, for the development of an ongoing manufacturing technology strategy, and gave NIST the authority to sponsor its own institutes when it could round up sufficient appropriations to do so, which it was able to accomplish in 2016. A notoriously divided Congress had come together on a bipartisan basis to bless advanced manufacturing and a creative model of MIIs to get there.

The Advanced Manufacturing Innovation Institute model

A key goal of the MIIs was to fill a gap in the US innovation system for manufacturing: to create a space where advanced manufacturing could evolve through a collaboration between industry (both small and large firms), universities and government (Molnar, Linder and Shuart, 2016). The federal award to each new institute over a five-year period was to range from USD 70 to USD 120 million. The consortium of firms, universities and state governments backing each new institute was required to contribute at least a one-to-one match to leverage the federal government's investment.

The complex institute model

This was a very complex model for the new institutes. The government's role here was not to make a single research award to a principal investigator to undertake a science research project according a carefully delineated plan in the grant application, which is the usual government R&D role. Instead the government's role had to relate to a large, complex mix of industrial firms that varied widely across numerous sectors and sizes, along with academic institutions that ranged from major research universities to regional universities to community colleges. And state governments were to be co-investors, with industry and the federal government supporting particular related projects. With the possible exception of Sematech,19 the federal government had not tried anything like this before.

The participant mix for the institutes was complex and so was their task list:

- "create" new production technologies, processes and "capabilities"
- serve as "proving grounds" to test new technologies and related processes
- support efforts to "deploy" for new production innovations
- "build workforce skills" to enhance production and processes for the emerging technologies.

The overall goal was to enable domestic manufacturing around the focused innovation area of each institute to flourish.

There was also to be a network of manufacturing institutes layered above the individual institutes, to enable cross-collaborations and exchanges of best practices. As advanced manufacturing took hold, a small or medium-sized manufacturer probably would not have just a 3D printing problem, it would have a range of future production challenges across a number of new fields, from digital production technologies to advanced materials. Production is also anchored in regions which tend to focus on particular production areas – e.g. cars in the Midwest, aerospace on the coasts and pharmaceuticals in the Northeast. While the institutes needed to have regional depth, they also had to translate their advances and know-how to manufacturers nationally. The institutes and their NNMI network had a major overarching assignment which was both regional and national.

The agencies take the lead: 2012

The institutes did not emerge from a highly-organised, well-timed governmental assembly line. They were scraped together. As noted in the previous section, after the 2010 elections there was a deep ideological divide in politics. Rather than wait for a divided Congress to authorise and fund a new programme, which could mean waiting forever, the new administration cajoled the agencies to start to set up institutes, using existing authority with funding scavenged from other areas. As a result, the agencies were in charge, and starting in 2012 picked focus areas for manufacturing institutes that matched their missions. The AMP1.0 report had assumed that the institute focus areas would come from a bottom-up model, with industry leading in selecting focus areas. Instead, there was a top-down approach, and the agencies decided the focus areas based on their own missions, not an overall manufacturing mission. This was not all bad. Since the agencies did the selection and were in charge, they chose focus areas they cared about that would serve their agency missions, potentially making this a more sustainable project over time, not a White House-imposed mandate. Over time, however, agency perspectives broadened. The top areas that industry had identified as its priorities in the AMP1.0 and AMP2.0 reports turned out to mesh over time with agency missions. And the agency lead tended to enhance agency buy-in for the new programme.

The US DoD had the most money so supported the most institutes. The US DoD had a rich history of wartime governmental economic interventions to assure technology and industrial outcomes, which no other agency dared politically to consider. The US DoD's Mantech programme, based in the Office of the Secretary of Defense, with branches in each of the military services, dated back many decades, but had not been a significant defence programme since at least the end of the Cold War.

But with the manufacturing institutes, Mantech now had a national mission overseen by the president himself.20 However, Mantech did not get a big new influx of funding, because of the Congressional impasse over all new programmes, so it had to rely on an

existing small staff and stretch existing budgets. Mantech's role was complicated by the reality that a number of connected programmes in the military services also had to be brought aboard. These separate programmes had separate service priorities, reporting systems and needs, and did not all exist in the Secretary of Defense's office.
One early development helped create interest in the US DoD. When the proposals came in for the first manufacturing institute on 3D printing (or additive manufacturing) established in 2012, the match proposed by industry and states to Mantech funds was not simply one-to-one: the institute proponents were ready to significantly overmatch. This was eye-opening to Mantech staff, as they could get major additional leverage on their investments. This opportunity for leverage, and to work on major new technologies at a larger scale, had not happened in Mantech in recent memory. Suddenly Mantech staff had a force multiplier.

The story at the US DoE was different. The US DoE's EERE office worked on applied energy technologies with industry. It had long had an industrial efficiency programme: industry had long been a major energy user and there were major clean energy gains, as well as potential savings to industry, from conservation and more efficient energy technologies. Importantly, in the absence of carbon pricing legislation in the United States, new energy technologies would have to compete in price with established fossil technologies. Unless production costs could be brought down for these new technologies, they would never get to the marketplace. Advanced manufacturing therefore became an important EERE priority.
The story at the Commerce Department's NIST was different, too. Despite NISTs' strong involvement in AMP, and its co-ordinating role among agencies, it was unable to secure Congressional funding until 2016 to establish a manufacturing institute. When it did, NIST avoided a "top-down" agency selection of the institute focus area, seeking "bottom-up" focus area proposals from industry and university consortia. NIST also played a supportive role in obtaining Congressional approval of the 2014 advanced manufacturing legislation, which focused on NIST.

While NSF was the fourth major federal government actor, its basic research focus limited its ability to form manufacturing institutes. However, NSF's Engineering Division was very involved in the AMP reports, led NSF programmes on advanced manufacturing research, and oversaw a number of engineering research centres focused on manufacturing technologies. In addition, NSF's Advanced Technology Education (ATE) programmes emphasised advanced manufacturing education and training in community colleges.

The manufacturing institutes: 2012-16

The manufacturing institutes are the centrepiece of the advanced manufacturing programme. The group of institutes was originally labelled the NNMI, but renamed ManufacturingUSA in 2016. The range of their technical focus is particularly notable; while Germany's "Industry 4.0" advanced manufacturing initiative emphasises the Internet of Things, i.e. only one of the areas addressed by the US institutes. The institutes' wide technical embrace is suggestive of how far-reaching an advanced manufacturing revolution could be. This technical breadth may be what is most interesting about the US approach, and deserves enumeration.

As of the beginning of 2017, there were a total of 14 institutes, eight sponsored by the US DoD, five by US DoE and one by NIST, with the option that NIST could add another in 2017 if funding proved available.[21] Two of the institutes and their technology areas are described

below, the first institute, America Makes – the National Additive Manufacturing Innovation Institute and, in the form of a more detailed case study, the Institute of Advanced Composites Manufacturing Innovation. A description of all the remaining institutes is provided in the annex to this chapter. The annex describes, the Digital Manufacturing and Design Innovation Institute (DMDII), the Lightweight Innovations for Tomorrow (LIFT) institute, which addresses lightweight and modern metals, Power America, for next-generation power electronics, the Institute for Advanced Composites Manufacturing Innovation (IACMI), the American Institute for Manufacturing Integrated Photonics (AIM Photonics), NextFlex, for flexible hybrid electronics, Advanced Functional Fabrics of America (AFFOA), the Smart Manufacturing Innovation Institute, the Rapid Advancement in Process Intensification Deployment Institute (RAPID), the Advanced Regenerative Manufacturing Institute (ARMI), the Institute for Reducing EMbodied Energy And Decreasing Emissions in Materials Manufacturing (REMADE) and the Advanced Robotics Manufacturing (ARM) Institute.

America Makes – National Additive Manufacturing Innovation Institute[22] – was the first manufacturing institute, announced in 2012, headquartered in Youngstown, Ohio, with a regional base in the Cleveland, Ohio to Pittsburg, Pennsylvania corridor, focused on 3D printing technologies, also known as additive manufacturing. Additive manufacturing is a process of joining materials to make devices using three-dimensional computer model data, layer upon layer. This compares with subtractive manufacturing which relies on traditional machine tools. It typically uses powder forms of metals or polymers, and even biological tissue. A competitive advantage of additive manufacturing is that parts can be fabricated as soon as the three-dimensional digital description of the part is entered into the printer, potentially creating a new market for on-demand, mass-customised manufacturing. Importantly, these processes minimise material waste and tooling requirements, as well as potentially compressing stages in the supply chain. These printing processes enable entirely new components and structures that cannot be cost-effectively produced from conventional manufacturing processes such as casting, moulding, and forging. Additive manufacturing might compete directly with mass production techniques if the speed of layering is significantly improved, although major progress on this is required. Meanwhile, additive manufacturing will be employed to replace parts on site, to reduce the need for parts inventories, and to create much more complex and intricate components beyond the reach of current processes. Additive manufacturing could be a key enabler of mass customisation (the ability to create small lots of personally designed products at the cost of mass produced goods). This could localise production, enabling scale-down of production for the first time in the history of production.

Selected after a highly competitive process, state and industry funds from the America Makes consortium, matched with support from the Air Force Mantech programme and other agencies, formed an approximately USD 100 million programme. The institute's mission is to accelerate additive manufacturing and its widespread adoption by bridging the technology gap between research and technology development and deployment. America Makes' roster of participants includes 53 companies, both small and large, concentrated mainly in the Midwest but stretching across the nation. These include firms organised around 3D printing technologies, like 3D Systems, major aerospace firms, like Boeing, Lockheed Martin, United Technologies and Northrup Grumman, where 3D printing may prove transformative, and a large number of small production firms. Some 36 universities are involved, ranging from major research universities to community colleges. Over 20 other organisations participate, from state agencies to industry associations.

The America Makes consortium has developed a detailed technology roadmap organised around design, materials, process and supply chain adoption. There is also an additive materials "genome" effort to enable step change improvements in the time and cost required to design, develop, and qualify new materials for additive manufacturing, using novel computational methods, such as physics-based and model-assisted material property prediction tools. The institute has worked to create an infrastructure for the sharing of additive manufacturing ideas and research, on development and evaluation of additive manufacturing technologies, on engaging with educational institutions and manufacturers for training in the new field, and on linking small and medium-sized firms with resources to enable them to use additive manufacturing. A major emphasis of American Makes has been on R&D and technology development projects, such as a joint university-industry effort between the University of Texas at El Paso, with Lockheed Martin, Boeing, Honeywell and

Draper Laboratory in Cambridge to embed a suite of electronics manufacturing technologies into 3D printing processes, such as precision machining, thermoplastic extrusion, direct foil embedding, wire embedding and wire management. There are over 30 other comparable joint university-industry development projects.

A manufacturing institute case study: The IACMI

To get a better idea of what is evolving in the institutes, this section looks at a single institute in more depth. The IACMI is headquartered in Knoxville, Tennessee.23 Its objective is to develop and demonstrate innovative technologies that will, within 10 years, make advanced fibre-reinforced polymer composites. Compared to existing techniques, it is intended to make such composites at 50% lower cost, using 75% less energy, and reusing or recycling more than 95% of the material.

Clear and unique institute focus. Institutes including IACMI are designed to address critical industry needs with a clear and unique focus. The objective IACMI is attempting to meet is the development of lightweight composites that offer significant benefits in energy efficiency and renewable power generation compared to current materials. This will require deployment of advanced technologies to make composites at a significantly lower cost, and more quickly, using less energy, and with the possibility of relatively easy recycling. Although there are numerous technical and institutional barriers, the field arguably offers significant opportunities for US industry.

Consortium approach. IACMI, like the other institutes, is based on a consortium across industry, universities and government. It includes large firms, such as Dow, Ford, General Electric, Dupont and Boeing, as well as smaller firms. A total of 57 firms are involved, reaching across the chemical, automotive and aerospace sectors. Overall, 15 universities, laboratories and colleges are involved, with university participants including the University of Tennessee, Pennsylvania State University, the University of Illinois, and Purdue University. State and other economic development entities are also engaged.

The core idea. The IACMI focus will be on dramatically lowering the overall manufacturing costs of advanced composites, cutting the energy required to form them and ensuring they are recyclable. It will create shared R&D and testing facilities and link leading industrial manufacturers, materials suppliers and university experts.

The industry value proposition. IACMI intends to offer four basic services to its industry partners:

- Access to shared R&D resources. Providing access to equipment, from laboratory level to full-scale production, to enable demonstration and testing and to reduce risk for industry investment.
- Applied R&D. Leveraging significant government R&D, plus cost sharing from industry, as well as academic investments, to create innovative solutions to challenges.
- A composites virtual factory. Giving access to end-to-end commercial modelling and

simulation software for composites designers and manufacturers through a web-based platform.
- Workforce training. Providing specialised training to prepare the current and future workforce for the latest manufacturing methods and technologies for advanced composites.

Addressing goals and challenges. IACMI has developed five- and ten-year technical goals: to reach 25% then 50% lower-carbon fibre-reinforced polymer (CFRP) cost; to reach 50% then 75% reduction in CFRP embodied energy requirements; and to reach 80% then 95% composite recyclability into useful products. The institute's impact goals, with a series of targets to be achieved over time, include: enhanced energy productivity; reduced lifecycle energy consumption; increased domestic production capacity; job growth and economic development.

Roadmap and strategic investment plans. IACMI will take a portfolio approach to projects. Its initial projects were identified in a proposal to the US DoE. These include strengthening infrastructure capacity for materials and processing as well as modelling and simulation, and workforce development in strategic areas. The aim is national benefit, including in automotive, wind and compressed gas storage sectors.

A second phase involves technology roadmapping, which is driven by IACMI's Chief Technology Officer, and an industry and technology advisory board. This phase will identify key hurdles to manufacturing high-impact, large-scale advanced composites and prioritise opportunities across the materials and manufacturing supply chain.

A third area requires development of a strategic investment plan, which will be driven by IACMI's board and its technical advisory board. The aim will be to change the innovation cycle to enable rapid adoption and scale-up of advanced composites manufacturing. Ongoing open project calls for technology development projects will align with the strategic investment plan and technology roadmap, with an emphasis on projects with high near-term impact.

Accelerating discovery to application to production. This will be a general goal, and like other institutes, the IACMI will seek to:
- Establish a presence, at scale, in the "missing middle" of advanced manufacturing research (TRL 4-7).
- Create an industrial commons, supporting future manufacturing hubs, with active partnering between stakeholders.
- Emphasise and support longer-term investments by industry.
- Combine R&D with workforce development and training.

An overarching objective will be the creation of new US advanced manufacturing capabilities and industries in composite materials.

This review of the IACMI's structure and aims illustrates approaches being adopted by many of the new manufacturing institutes. However, the institute model is flexible, depending on the sector to be served, and can significantly vary.

Lessons learned by the manufacturing institutes

As has been mentioned earlier, the manufacturing institute programme was established very rapidly by the Obama administration at the president's personal direction in response to a policy crisis – a major decline in a key economic sector, manufacturing, in the aftermath of the 2008-09 recession. Because of Congressional deadlock, the administration was unable to start with a clean slate and design and implement a completely new programme. Instead it had to turn for funding and organisation to existing agencies with their existing programmes and funding, grafting new programmes onto established organisations. So the large foot of a new programme for manufacturing innovation had to be squeezed into existing agency programme shoes. Needless to say, it could not be a perfect fit.

Like any new programme, some of the experimental pilots will fail and some will succeed. Only a few of the new institutes have been around long enough to have their progress evaluated against their mission statements. The other institutes are still infants. Transforming a massive economic sector like manufacturing through innovation is not a short-term project. Clearly, there has been major progress in getting off the ground R&D and technology strategies in a range of new technology areas that could dramatically affect the future of manufacturing. One can now see a new set of lessons from various institutes as well as challenges that have come up as the institutes have evolved. These challenges, and a consideration of how to meet them, are set out below. Some institutes are already addressing many of these challenges, but others may now also need to address them. So the list below, developed from discussions with institute leaders, federal agency officials and participating university experts, represents early lessons learned which are starting to be applied to the evolving in-state network.

Orientation to technology versus production

The manufacturing institutes created to date are working in topic areas selected by the public R&D funding agencies. These topic areas reflect the agency missions, but not necessarily the priority needs of the particular manufacturing sector. Accordingly, the choice of topic areas has risked being more oriented to technology development as understood by agencies than by industry. This has tended to self-correct: agencies are increasingly soliciting industry perspectives.

To avoid these issues, the AMP2.0 report identified core criteria for selecting focus areas for advanced manufacturing institutes ("manufacturing technology areas" [MTAs]). While not formally applied by the agencies, these remain illuminating and relevant. The four criteria were:

- **Industry or market pull.** Does there exist a current "pull" or demand for this MTA by industry? If industry is not yet adopting this MTA, is there a strong perceived pull by the

market or consumers?
● **Cross-cutting.** Does this MTA cut across many sectors (automotive, aerospace, biotech, infrastructure), and across multiple sizes of manufacturers in the supply chain network?
● **National or economic security.** Does failure to have US competence or dominance in this MTA pose a threat to national security or to economic security? Does lack of a US competence severely disadvantage US competitiveness in the supply network?

● **Leveraging US strengths**. Does this MTA leverage an already available workforce and education system, unique infrastructure, or policies? (PCAST, 2014).
If additional institutes are created, agencies could be encouraged to more formally weigh the AMP2.0 criteria in their topic selection process to ensure the match between industry and agency needs.

The limitation of federal support to five years
Starting with the announcement of the first manufacturing institute, America Makes, there has been a requirement that the institutes be self-sustaining (without federal funding) after five years. The Revitalise American Manufacturing Act, passed in 2014, likewise adopts a five-year term for federal support to manufacturing institutes created by NIST.

This approach follows the Sematech model, where DARPA's funding for the Sematech semiconductor industry consortium ended after five years. But the institute idea itself derives from, as discussed below, Germany's Fraunhofer Institutes, which face no such cut off of support after a short fixed term, from their federal government. The assumption that the institutes can become financially independent in five years is problematic. Reinvigorating manufacturing innovation is going to be a long term not a short-term project and requires realism about technology and business challenges.

Most of the technologies that the new institutes are being organised around will require a longer-term evolution than the five-year term currently fixed for federal support before they are ready for implementation at scale. Given the evolving development of the institutes, some mechanism for continued federal cost sharing will probably be required for a significant additional period beyond the initial five years. This could take the form of an evaluation process after five years with an opportunity for an institute to obtain a renewed term of funding if performance has been successful. Or, institutes, as they approach the end of their initial term, could compete for awards from an agency source of multi-year R&D federal funding, available to pursue technology development projects and, potentially, related training projects.

The research governance model
The manufacturing institutes were formed by federal mission agencies, and these

carried over their regulatory and organisational perspectives as the institutes developed. Agencies have tended to treat and manage their institutes in ways they are familiar with, as research recipients. So the agency governance model is effectively an R&D supervisory model (through co-operative agreements), and agencies tend to see their role as research supervisors. Yet the role of the institutes is much broader. This role involves building lasting collaborations with support systems across a wide range of firms and researchers in many sectors, not only for research but also for testing, technology demonstration and feedback, product development, and workforce education and training.

The institutes' intended role is very complex and ambitious, and requires a different governance and support model than more straightforward research projects. To summarise, the governance system for federal research in many cases may not foster the kind of collaboration required for the non-research aspects of the institutes' tasks, and may not prepare the institutes to be financially self-sustaining after five years. Thought needs to be given to how the governance model is working, including administrative delays

in standing up new institutes. Should, for example, the cost-share funding from industry and states be controlled by the agency, or should the institutes set these parameters with the contributing stakeholders? Could the agencies shift from traditional research contract supervision and oversight to encourage a more collaborative model with growing state and local government, and especially industry, involvement?

Support from the network

The AMP2.0 report recommended that the growing group of manufacturing institutes be joined together into a supporting network. The report proposed, "a governance structure that maintains autonomy for individual institute operations while creating a public-private network governing council that oversees the broader performance of the network and the sustainability of the individual institutes." (PCAST, 2014). NIST is working to implement this recommendation, through the Manufacturing USA network. As NIST well understands, the network can serve a range of needs. As each new institute is established, it should not have to "reinvent the wheel." Many lessons have been learned about how to constitute governing boards and legal structures, how to manage intellectual property, how to set up tiers of participants, how to organise regional outreach and education efforts, and so forth. A strong, supportive network organisation could help ensure that common problems are shared by the institutes and tackled in common, and that best practices and lessons learned by individual institutes are studied and shared across the network.

Emphasis on R&D versus implementation

The AMP1.0 report envisioned institutes organised at TRL 4-7 ("Technology development" to "Technology demonstration" to "System and subsystem development") (PCAST, 2012). The supporting federal agencies have tended to organise the institutes around technology development for new technologies consistent with their missions, which is still some distance from industry implementation. This development focus may be inevitable given the gap in US R&D on manufacturing, but over time this will create an implementation gap in the role of the institutes. Without more process technologies, demonstration, testing and feedback systems, the institutes may limit their ability to bring in small and mediumsized manufacturing firms because sought-after technologies are not ready for these stages, where the smaller firms could pick them up. This will limit technology dissemination. Most institute leaders understand this well, but the issue continues to need focus.

In summary, the technology development role of the institutes is clearly important and central. However, the institutes need to be sure to build in the additional tasks required for TRL levels 5-7, further down the innovation pipeline, so the evolving technologies can be implemented, especially by smaller and medium-sized firms. The institutes are working to ensure this, but their evolving approaches need to be shared and compared.

Supply chain involvement

Institutes, as suggested above, have often focused initially on project calls for technology R&D that typically involve university and major firm researchers; smaller firms are usually not included because they have limited R&D capability. Yet the new technologies will not be adopted unless integrated supply chains including smaller firms are brought in to understand and use them. For this to occur, the institutes will need to embrace more of a full supply chain approach, with supply chains engaged in technology demonstration, testing and training.

Workforce training and education

There is a similar potential problem for the role of the manufacturing institutes in workforce training and engineering education. Without engineering teams and a workforce skilled in the new technologies, in small as well as large firms, the evolving advanced manufacturing technologies simply cannot be widely implemented. Some institutes have seen that workforce training can be an early success for the institutes in serving their industrial constituents and sectors, and building networks of contacts with a wide range of firms. This is a particularly important way for the institutes to engage with both smaller firms and states, which play a role in workforce education through their community college systems. However, this has not always been the case. Agency contract and programme officers for the institutes tend to be technologists, not education experts, so many focus on the R&D side of the institute role. However, institutes need to master both sets of tasks to fully serve their industry sectors. The agencies should ensure a workforce education and training focus across the institutes. In fact, the evolving NNMI network could play a constructive role in introducing best education practices across the institutes.

The role of the United States

From the outset, participants in the AMP1.0 and 2.0 processes, including government, industry and universities, saw a critical challenge of balance for the institutes. All manufacturing, in the end, is embedded in production and innovation ecosystems that are very regional. So the manufacturing institutes must keep one leg in regional manufacturing economies, which is where their industry and university constituencies are located. Yet the technologies the institutes are developing will also be needed nationally. 3D printing, for example, will not be just needed in northeast Ohio, it will be needed nationally and in many industrial sectors. Keeping one leg in regional economies and the other leg in the national economy creates a complicated, bifurcated model for the institutes.

Another issue some of the institutes are facing is that with a strong emphasis on R&D projects as their initial focus, they may be too tilted towards a national approach and need more balance. If federal support ends after a five-year term, the regional and local role the institutes can play becomes vital. Accordingly, support from states could be key to an institute's survival. If the institutes are not closely tied early on to regional economies, the support from states will simply not develop to the depth necessary. Some institutes are creating models for how to do this. LIFT, for example, has been particularly successful in bringing in its participating states and their community colleges into the fold to build workforce education programmes, a state priority. IACMI has been effective in creating operating nodes supported in its participating states to more effectively involve them.

In summary, building state support by tying in to regional economies will be key for institute survival. For new government programmes to survive and thrive they not only need a strong substantive policy design, they must have a sound political support design that will sustain them. The political design is not easy: it must not distort the substantive policy design to serve political ends. Indeed, the political design must support the substantive policy design, but still build support to sustain it (Bonvillian, 2011). The institutes need to find the right mix of political and substantive design. Developing a regional economic focus is not only important for the substantive model of a sustainable, viable institute, it is also important to the political aspect of future support.

An underlying problem: Historically insufficient federal R&D for advanced manufacturing

A significant issue that affects the ability to meet a number of challenges discussed above is the lack of past focus by federal R&D agencies on research on manufacturing. As discussed in earlier sections, successive federal governments in the United States assumed that manufacturing leadership was a given, and did not feel the need to make it a focus of R&D policy. That is part of the reason why the manufacturing institutes tend to focus more on earlier technology development stages rather than the additional focus on technology implementation as was proposed in the AMP report. And foundational research in manufacturing technologies is also still needed. If ongoing federal mission agency R&D can focus more on enabling technologies in manufacturing, that could be an important complement to the manufacturing institutes, helping to create new manufacturing technology paradigms. To be clear, ongoing federal research has supported major advances in such areas as digital and sensor technology, advanced materials, photonics, robotics, flexible electronics and composites. This has helped the technology community in the United States see that potential manufacturing paradigms are in sight, which is a major part of what makes this effort so interesting. However, without strong R&D input into the institutes, their technology development and implementation roles will lack a continuing foundation.

The government has taken important initial steps down this pathway of translating research towards the institutes. In April 2016, the Subcommittee on Advanced Manufacturing (SAM) of the National Science and Technology Council (an arm of OSTP used for inter-agency collaborations) released a report entitled "Advanced Manufacturing: A Snapshot of Priority Technology Areas Across the Federal Government." (NTSC, 2016). While this effort has not linked the federal R&D portfolio to the institutes, it has at least identified many relevant ongoing R&D programmes that could be better linked. This task requires further attention.

Lessons from Fraunhofer

Finally, there are important lessons from Germany's Fraunhofer Organisation and Fraunhofer Institutes, which served as the model for the US institutes. Although the Fraunhofer Institutes have significant autonomy, the overall organisation allows participatory governance, as well as sharing of practices and research. The US institutes could benefit from a strong institute network, providing both access to best practices and a shared governance model. With the development of the institute network, Manufacturing USA, in 2016, NIST began to pursue this task, asking the institute directors to take leadership, which could enable sharing of practices and collaborative programmes across institutes. The continuing central government support of Fraunhofer Institutes, which is not termrestricted as in the United States, has been critical for their sustainability and strength, which the United States now needs to consider.

In addition to a working network, the institutes need a continuous learning capability to stay ahead of issues, a role which the Fraunhofer system has performed, lately in co-ordination with larger government projects on "Industry 4.0" advanced manufacturing. NIST and NSF have therefore also created a "think and do tank," MForesight – the Alliance for Manufacturing Foresight – to continuously evaluate technical and policy issues the institutes as a group face. MForesight seeks to provide "ideas and insights to business and government decision makers on emerging technology trends and opportunities for public-private investments in advanced manufacturing." (MForesight, 2017). Its portfolio of study projects also aims to promote technology innovation that can bridge the gap between research and manufacturers.

Conclusion

After a steep decline in its manufacturing sector in the decade of the 2000s, the United States is now playing manufacturing catch-up. As detailed above, the decline was characterised by a loss of 5.8 million manufacturing jobs, declining capital investment, declining output and, because of lower output, lower productivity than had been estimated. As economist David Autor and colleagues have delineated, the decline in manufacturing was also characterised by significant social disruption, through trade imbalances with China in manufactures.

If the United States is to compete with low-wage, low-cost competitors abroad, it must raise production efficiency to offset its higher costs, which means it must have a manufacturing innovation strategy. There are no real policy substitutes. Tax, trade and macroeconomic policy can improve the competitive posture of US manufacturing at the margins but cannot significantly raise productivity and efficiency. Innovation in production technologies and processes, with accompanying business models to implement them, appear key.

The government began to focus on an innovation initiative for manufacturing in a 2011 PCAST report on "Ensuring American Leadership in Advanced Manufacturing". The policies were fleshed out in two PCAST reports in 2012 (on capturing domestic competitive advantage in advanced manufacturing; PCAST [2012]) and 2014 (on accelerating US advanced manufacturing"; PCAST [2014]), prepared by the president's Advanced Manufacturing Partnership, a collaboration between leading firms and universities. While AMP proposed numerous approaches, the centrepiece was the advanced manufacturing institute concept, which the administration quickly acted on and began to implement well before the first AMP report was released in 2012.

The effort to establish a network of advanced manufacturing institutes got off to a promising start, attempting to address a critical gap in the US system for manufacturing innovation. It was a complex and challenging organisational model, requiring groups of firms, both small and large, as well as university researchers and states, to collaborate and cost share, under guidance from federal R&D agencies not used to managing such large teams.

The basic institute structure is now falling into place, and focused initially on manufacturing technology development projects. However, an opportunity exists to consider a second stage of enhancements to the model. The institutes face a series of challenges, as described above, that can now be considered as they continue to scale up and mature:

- Improve the current research agency and institute governance model.
- Continue federal government support after the initial five-year commitment.
- Create a strong network of institutes where best practices in research and workforce education advances can be shared.

- Create an emphasis within the institutes on technology implementation at later TRLs as well as technology development.
- Ensure that institutes emphasise (and collaborate) on optimal workforce training and education approaches.
- Ensure linkages between institutes and regional economies, in addition to serving manufacturing technology development at the national level.

In addition, federal R&D from mission agencies in the area of advanced manufacturing technologies could be better connected to the institutes. It would help, in particular, if

these funds flowed in on a continuing basis, so that the technologies at the institutes do not get stranded but keep improving. Of course, the United States now has few options other than pursuing and upping its capabilities in advanced manufacturing, since its leading competitors are pursing somewhat similar strategies (see e.g. Forschungsunion and Acatech [2013], Kennedy [2015], Xinhua [2015], Xinhua [2016], Whang [2012], Manufacturing Technology Centre [2016], Catapult High Value Manufacturing Centres [2016] and Shipp [2012]).

The decline of manufacturing in the United States in the decade of the 2000s, has led to a new strategy for manufacturing based on innovation. This strategy for advanced manufacturing was recognised as one among a series of approaches, needed to restore US production strength, from tax, trade and macroeconomic policy to new ways of providing training. But this new innovation policy was unlike anything that had been tried before by the United States in its manufacturing sector. The advanced manufacturing policy required a complex and challenging innovation organisation model, joining industries small and large, university research and federal and state government agencies in the common pursuit of new production technologies and processes. The policy sought a new competitive formula by raising production efficiency and productivity. The support for advanced manufacturing has been an attempt to apply an historic US economic strength – its innovation system – to an entirely new set of problems.

Notes

1. This chapter draws from the author's upcoming article in Annals of Science and Technology to be published in the first quarter of 2017, and will be elaborated on in an upcoming book on this subject with Peter L. Singer, to be published by MIT Press, planned for autumn 2017.
2. Bureau of Labor Statistics (BLS), Current Employment Statistics (CES) (manufacturing employment), http://data.bls.ces. See also the detailed review of manufacturing job loss in Atkinson et al. (2012) and Scott (2015).
3. Bureau of Labor Statistics (BLS), Current Employment Statistics (CES) (manufacturing employment), http://data.bls.ces.
4. Bureau of Economic Analysis (BEA), Fixed Assets Accounts (investments in private fixed assets by

industry, http://bea.gov. See also Atkinson et al. (2012), pp. 47-58.
5. Bureau of Labor Statistics (BLS), Labor Productivity and Costs, Productivity change in the manufacturing sector (database), www.bls.gov/lpc/prodybar.htm.
6. Bureau of Economic Analysis (BEA), Foreign Trade, Exports, Imports and Balance of Goods by Selected NAICS-Based Product Code, Exhibit 1 in FT-900 Supplement for 12/15, 5 February 2016, www.census.gov/foreign-trade/Press-Release/2015pr/12/ft900.pdf.
7. Bureau of Economic Analysis (BEA), Trade in Goods with Advanced Technology Products, 2015, Exhibit 16, www.census.gov/foreign-trade/balance/c0007.html.
8. Bureau of Economic Analysis (BEA), US International Trade in Goods and Services, Exhibit 1, 5 February 2016, www.census.gov/foreign-trade/Press-Release/2015pr/12/ft900.pdf.
9. For a discussion of disruptive societal effects of US manufacturing decline, see Bonvillian (2016).
10. Bureau of Labor Statistics (BLS), Industries at a Glance, Manufacturing: NAICS 31-33, Workforce Statistics (July 2016), www.bls.gov/iag/tgs/iag31-33.htm.
11. The developments reviewed in this subsection, and sources discussing them, are detailed in, Bonvillian 2014.
12. This "industrial policy" concern remains embedded in partisan US politics. Although the manufacturing institutes created in the 2012-16 period, as discussed below, could be branded in this way, the crisis in manufacturing employment and plant closings tended to overcome such concerns, and bipartisan legislation supporting the institute model passed, as noted below, in 2014. In addition,

the institutes are designed to be industry-led, industry cost-shared, and collaborative, not government-dominated.
13. In this period there were a number of significant articles on the predicament of US manufacturing that provided a foundation for the studies reviewed below, although the MIT study discussed below was the most extensive. These other articles included: Tassey (2010); Fuchs and Kirchain (2010); Houseman et al. (2011); Breznitz and Cowhey (2012); Atkinson et al. (2012); Helper, Kruger and Wial (2012); Shipp et al. (2012); Bonvillian (2012); and Pisano and Shih (2012).
14. Names of AMP1.0 Steering Committee members from companies and universities can be found in, The White House, Office of the Press Secretary, Press Release, "Report to President Outlines Approaches to Spur Domestic Manufacturing Investment and Innovation, 12 July 2012, www.whitehouse.gov/the-press-office/2012/07/17/report-president-outlines-approaches-spur-domesticmanufacturing-
investm.
15. 15 In the US, both the US Department of Defense (US DoD) and the National Aeronautics and Space Administration (NASA) have developed similar but somewhat different TRLs. The AMP applied the US DoD terminology (see US DoD [2011]).
16. See also the statement on the PIE website, http://web.mit.edu/pie/research/index.html.
17. See e.g. Deloitte and the Manufacturing Institute (2011). This work found that 82% of senior executives in manufacturing reported moderate to serious gaps in the availability of qualified, skilled candidates. 74% of manufacturers reported that these shortages affected their ability to expand operations.
18. See S.1468, 113th Congress, 2nd Session, www.govtrack.us/congress/bills/113/s1468/text; HR 2996, Revitalize American Manufacturing and Innovation, 113th Congress, 2nd Session, Congress.gov, bill actions, www.congress.gov/bill/113th-congress/house-bill/2996/actions.
19. Sematech was a consortium of semiconductor fabricators and equipment makers that in the 1990s was facing imminent demise from strong competitors in Japan. Industry funding was matched by the Defense Advanced Research Projects Agency (DARPA). The consortium focused on major efficiency and quality improvements in semiconductor manufacturing; after five years production leadership was restored and DARPA funding ended. Sematech continued as a key technology

planning organisation to keep the industry on a Moore's Law roadmap.
20. Aside from Mantech, DARPA's Deputy Director was involved in the AMP1.0 effort, and DARPA led a sizeable portfolio of DARPA advanced manufacturing R&D and advised on the AMP reports.
21. Descriptions of the institutes draw from each of their websites. Descriptions of the manufacturing technologies they aim to advance are drawn from NTSC (2016), pp. 36-39.
22. Information in this section is drawn from the America Makes website, www.americamakes.us/about/overview.
23. This section is drawn from NIST (2016).

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ANNEX 11.A.1
Description of the advanced manufacturing institutes

This annex describes the 12 advanced manufacturing institutes not described in the main body of this chapter:

The Digital Manufacturing and Design Innovation Institute (DMDII) was formed in 2014 with a hub located in Chicago. Digital manufacturing involves the use of integrated computer-based systems, including simulation, three-dimensional visualisation, analytics and collaboration tools, to create simultaneous product and manufacturing process definitions. Design innovation is the ability to apply these technologies, tools, and products to reimagine the entire manufacturing process from end-to-end.

DMDII has 201 members, including major firms from a wide range of sectors, numerous smaller firms and 11 universities. Its USD 70 million in US DoD Army Mantech funding was matched with industry and state funding of USD 248 million. DMDII's mission is digital manufacturing to lower product design costs by fostering deep connections between suppliers. It also aims to lower production costs and reduce capital requirements, through better linkages from end-to-end of the product life cycle. Cutting time to market through faster iterations, developing and implementing innovations in digital design, digital factories and digital supply chains are also goals. Overall, it seeks to develop both new products and improve legacy products.

Lightweight Innovations for Tomorrow (LIFT) addresses lightweight and modern metals, was founded in 2014. Its hub is in Detroit, Michigan, supplemented with locations in Michigan, Ohio, Indiana, Tennessee, and Kentucky. Lightweight and advanced metals offer major performance enhancements and greater energy efficiency that can improve the performance of many systems in defence, energy, transportation and general engineered products. Lightweight metals have applications in wind turbines, medical technology, pressure vessels, and alternative energy sources.

LIFT has 78 members, from a wide range of firms, small and large, including metals and aerospace firms and automotive suppliers, and 17 universities, which matched USD 70 million in federal funds from the Navy Mantech programme and the Office of Naval Research. LIFT's mission is to innovate in lightweight high-performing metals production and enable the resulting technologies to be applied across industries. LIFT is working on projects in melting, thermo-mechanical processes, powder processing, agile low-cost tooling, coatings, and joining, with widespread applications in automotive, aerospace, ship building, railroads, fabrication and other sectors.

Power America – for next-generation power electronics was created in 2015 to develop wide bandgap semiconductor technology. This could enable a major increase in the energy efficiency and reliability of power electronics through smaller, faster and more efficient semiconductor materials. These non-silicon-based technologies are able to operate at higher temperatures, can block higher voltages, switch faster with less power loss, are potentially more reliable and carry substantial system-level benefits. These capabilities make it possible to reduce weight, volume, and life-cycle costs in a wide range of power applications. Such semiconductor technology will have many applications, including in industrial motor systems, consumer electronics and data centres, and in conversion of renewable energy sources (solar and wind). If widespread adoption of these technologies could be accomplished in even a few applications, then very significant electrical power savings, including in industrial production, could be achieved. The higher cost of wide bandgap technologies is expected to decline as higher production levels are achieved.

Supported by the Department of Energy's Energy Efficiency and Renewable Energy Advanced Manufacturing office, Power America includes 17 industry partners, five universities and three laboratories, and is based in Raleigh, North Carolina.

The Institute for Advanced Composites Manufacturing Innovation (IACMI) was formed in 2015 to develop and demonstrate technologies that will make advanced fibre-reinforced polymer composites at 50% lower cost, using 75% less energy, with 95% or more reuse or recycling of material within a decade. The IACMI is headquartered in Knoxville, Tennessee. Lightweight, high-strength, and high-stiffness composite materials have been identified as a key technology that can cut across industrial sectors, with the potential to achieve a more energy-efficient transportation sector, enable efficient power generation, and increase renewable power production. The range of lightweight, high-strength composite applications is vast, from autos, to aircraft, to wind blades. The challenges include high costs, low production speeds (long cycle times), high manufacturing energy intensity for composite materials, recyclability, and a need to improve design, modelling and inspection tools and meet regulatory requirements. Technology acceleration and manufacturing research is needed to meet production cost and performance targets, from constituent materials production to final composite structure fabrication.

The IACMI was supported by a USD 70 million award from the Department of Energy's Energy Efficiency and Renewable Energy Advanced Manufacturing office, which was matched by USD 180 million. The IACMI includes 57 companies, 15 universities and laboratories and 14 other kinds of entities.

The American Institute for Manufacturing Integrated Photonics (AIM Photonics) was formed in 2015 with hub locations in Albany and Rochester, New York. Its goal is to foster ultra-high-speed transmission of signals for communications, new high-performance computing and sensors, and imaging for health sector advances.

Integrated photonics requires the integration of multiple photonic and electronic devices (e.g. lasers, detectors, waveguides and passive structures, modulators, electronic controls, and optical interconnects) on a single substrate with nanoscale features. The benefits of integrating these components could be very significant: simplified system design, improved system performance, reduced component space and power consumption, and improved performance and reliability, which will enable important new capabilities and functionality with lower costs. The current photonics manufacturing sector is a collection of interrelated but largely independent businesses, organisations and activities. The sector is a

potential ecosystem, but lacks the organisation and aggregated market strength needed to efficiently innovate manufacturing technologies for cost-effective design, fabrication, testing, assembly, and packaging of integrated photonic devices.

AIM Photonics is to focus on building an end-to-end photonics ecosystem, including domestic foundries, integrated design tools, and automated production packaging, assembly and testing, as well as workforce development. The federal award was matched by over USD 200 million in state and industry support.

Flexible Hybrid Electronics (NextFlex) was formed in 2015 with a hub in San Jose, in Silicon Valley. Its goal is to produce highly tailorable devices on flexible, stretchable substrates that combine thin complementary metal oxide semiconductor technology for constructing integrated circuits components with new components added through printing processes. These represent flexible and hybrid features for circuits, communications, sensing and power sources that are unlike current silicon processors.

Flexible hybrid electronics would preserve the full operation of traditional electronic circuits, but in novel flexible architectures that could be part of curved, irregular and stretched objects. They could expand traditional electronic packaging to new forms, enabling new commercial and defence technologies. Examples include medical devices, prosthetics and sensors, sensors to monitor structural or vehicle performance, sensors interoperating through the Internet or as sensor clusters to monitor physical positions, wearable performance or information devices, human-robotic interface devices, and lightweight human-portable electronic systems.

The US DoD Mantech award was for USD 75 million, with an industry and state and local government cost share of USD 96 million. NextFlex includes 22 member companies ranging from semiconductor firms and their suppliers, to companies in aerospace and the life sciences. Also included are 17 universities, and state and regional organisations.

Advanced Functional Fabrics of America (AFFOA) was launched in April 2016 and commenced its start-up period, with over 80 members, as of the end of 2016. The institute

is headquartered in Massachusetts, and plans a series of regional nodes.
Scientific advances have enabled fibres and textiles with extraordinary properties including increased strength, flame resistance, and electrical conductivity. Such fibres could become electronic, sensor and communications components. This new range of fibres and textiles are composed of speciality fabrics, industrial fabrics, electronic textiles, and other forms of advanced textiles. They could provide communication, lighting, cooling, health monitoring, battery storage and many more new functions. These technical textiles are built on a foundation of synthetic, natural fibre blends and multi-material fibres that have a wide range of applications, in commercial and defence sectors, which go far beyond traditional wearable fabrics.

AFFOA headquarters are in Cambridge, Massachusetts, and it combines USD 75 million in US DoD Mantech funds with some USD 240 million in industry and state support. AFFOA aims to serve as a public-private partnership to support an end-to-end innovation ecosystem in the United States for revolutionary fibres and textiles manufacturing. The institute also aims to use domestic manufacturing facilities to develop and scale up manufacturing processes. It plans to provide rapid product realisation opportunities, based on design and simulation tools, pilot production facilities, a collaborative infrastructure for suppliers, and workforce development opportunities. The institute wants to effect a revolution in fibre and textiles, incorporating IT advances and integrating intelligent devices with fibres.

The Smart Manufacturing Innovation Institute was announced in June 2016 and is now in its start-up phase and is setting membership (The White House, 2016). The institute is headquartered in Los Angeles.

Smart manufacturing can be characterised as the convergence of information and communications technologies with manufacturing processes, to allow a new level of realtime control of energy, productivity, and costs across factories and companies. Smart manufacturing was identified by the AMP2.0 report as a high-priority manufacturing technology area in need of federal investment. Being able to combine advanced sensors, controls, information technology processes and platforms, and advanced energy and production management systems, smart manufacturing has the potential to increase energy efficiency and manufacturing capability in a wide range of industrial sectors.
Of the USD 140 million Smart Manufacturing Innovation Institute budget, USD 70 million over five years is already appropriated federal funding from the Energy Department's Advanced Manufacturing Office. The remainder is in matching funds. The Smart Manufacturing Innovation Institute will focus on integrating information technology in the manufacturing process through devices like smart sensors that reduce energy use. For example, the institute plans to partner with the US DoE's Institute for Advanced Composites Manufacturing Innovation to test advanced sensors in the production of carbon fibre. The

Smart Manufacturing Innovation Institute expects to partner with more than 200 companies, universities, national laboratories and non-profits. Microsoft Corp., Alcoa Inc., Corning Inc., ExxonMobil, Google, the National Renewable Energy Laboratory and numerous smaller firms are among the Smart Manufacturing Innovation Institute partners. The institute plans to launch five centres, focusing on technology development and transfer and workforce training, in regions around the country, headed by universities and laboratories in California (UCLA), Texas (Texas A&M), North Carolina (NC State University), New York (Rensselaer Polytechnic Institute), and Washington (Pacific Northwest National Laboratory).

The Rapid Advancement in Process Intensification Deployment Institute (RAPID): on 9 December 2016, the EERE office announced that a consortium led by the American Institute of Chemical Engineers would form the fourth institute sponsored by the Department of Energy, calling it a critical step in the administration's effort to double US energy productivity by 2030. Leveraging up to USD 70 million in federal funding with a higher level of private cost-share commitments from over 130 partners, RAPID will focus on developing breakthrough technologies to boost domestic energy productivity and energy efficiency by 20% in five years through manufacturing processes in industries such as oil and gas, pulp and paper and various domestic chemical manufacturers.

Traditional chemical manufacturing relies on large-scale, energy-intensive processing. The new institute will leverage approaches to modular chemical process intensification – including combining multiple, complex processes such as mixing, reaction, and separation into single steps – with the goal of improving energy productivity and efficiency, cutting operating costs and reducing waste. Process breakthroughs can dramatically shrink the footprint of equipment needed on a factory floor or eliminate waste by using the raw input materials more efficiently. For example, by simplifying and shrinking the process, this approach could enable natural gas refining directly at the wellhead, saving up to half of the energy lost in the ethanol cracking process today. In the chemical industry alone, these technologies could save more than USD 9 billion annually in US processing costs.
The National Institute for Innovation in Manufacturing Biopharmaceuticals (NIIMBL): on 16 December 2016, Secretary of Commerce Penny Pritzker announced an

award of USD 70 million to the new NIIMBL institute. This is the first institute with a focus area proposed by industry and the first funded by the Department of Commerce. The agency developed an "open topic" approach, where a new institute could cover any area not currently targeted by an existing institute. NIST had launched an "industry-proposed institutes competition" as a way to allow a bottom-up topic selection process to allow industry-led consortia to propose technology areas seen as critical by regional manufacturers. NIIMBL was the result.

NIIMBL will aim to transform the production process for biopharmaceutical products.

Overall, it will seek to advance US leadership in the biopharmaceutical industry, improve medical treatments and ensure a qualified workforce by developing new training programmes matched to specific biopharmaceutical skill needs. The announcement was made at the University of Delaware, which will co-ordinate the institute in partnership with the Department of Commerce's NIST. In addition to the federal funding, the new institute is matched by an initial private investment of USD 129 million from a consortium of 150 companies, educational institutions, research centres, co-ordinating bodies, nonprofits and manufacturing extension partnerships across the country.

The Advanced Regenerative Manufacturing Institute (ARMI): on 21 December 2016, the Department of Defense announced an award to establish ARMI at a White House event celebrating the progress the National Network for Manufacturing Innovation, now Manufacturing USA, has made. This new institute was the seventh led by the US DoD. New Hampshire's US senators and its governor joined in a parallel, in-state, bipartisan announcement of the USD 80 million, five-year award to establish the biomanufacturing consortium, which will be headquartered in the Manchester Millyard. The institute – led by a coalition that includes DEKA R&D Corporation, the University of New Hampshire and Dartmouth-Hitchcock health care system – is tasked with developing and biomanufacturing tissues and organs that can be transplanted into patients. DEKA founder Dean Kamen will direct the institute. It would pioneer next-generation manufacturing techniques for repairing and replacing cells and tissues. If successful, such technology could lead to the ability to manufacture new skin or life-saving organs for the many Americans stuck on transplant waiting lists. The institute will focus on solving the cross-cutting manufacturing challenges that stand in the way of producing new synthetic tissues and organs, such as improving the availability, reproducibility, accessibility, and standardisation of manufacturing materials, technologies and processes. Collaborations are expected across multiple disciplines, from 3D bioprinting, cell science and process design, to automated pharmaceutical screening methods, to the supply chain expertise needed to rapidly produce and transport these life-saving materials.

Reducing Embodied Energy and Decreasing Emissions (REMADE) in Materials Manufacturing, formed by the US DoE, was selected on 4 January 2017, to be headquartered in Rochester, New York and led by the Sustainable Manufacturing Innovation Alliance. REMADE will leverage up to USD 70 million in federal funding, subject to appropriations, and will be matched by USD 70 million in private cost-share commitments from over 100 partners. REMADE will focus on driving down the cost of technologies needed to reuse, recycle and remanufacture materials such as metals, fibres, polymers and electronic waste and aims to achieve a 50% improvement in overall energy efficiency by 2027. These efficiency measures, the US DoE indicated, could save billions in energy costs and improve US economic competitiveness through innovative new manufacturing techniques.

It would aim to reduce the total lifetime energy use of manufactured materials via reuse and recycling. The institute will focus on reducing the total lifetime use of energy in manufactured materials by developing new cradle-to-cradle technologies for the reuse, recycling, and remanufacturing of manmade materials. US manufacturing consumes nearly one-third of the nation's total energy use annually, with much of that energy embodied in the physical products made in manufacturing. New technologies to better repurpose these materials could save US manufacturers and the nation up to 1.6 quadrillion British thermal units of energy annually, equivalent to 280 million barrels of oil, or a month's worth of oil imports.

The US DoD proposed the **Advanced Robotics Manufacturing Institute (ARM)** to focus on building US leadership in smart collaborative robotics, where advanced robots work alongside humans seamlessly, safely, and intuitively to do the heavy lifting on an assembly line or handle with precision intricate or dangerous tasks. The US DoD indicated assistive robotics has the potential to change a broad swath of manufacturing sectors, from defence and space to automotive and health sectors, enabling the reliable and efficient production of high-quality, customised products.

ARM, the 14th and last Manufacturing USA Institute to be announced by the Obama administration was named on 13 January 2017. It will be headquartered in Pittsburgh, and the proposal group was convened by Carnegie Mellon University. The institute will bring together a very large team, including 84 industry partners, 35 universities and 40 other groups in 31 states. Federal funds plus industry and state cost sharing will total some USD 250 million; the federal commitment is for USD 80 million. Clemson University's Center for Workforce Development will lead the new institute's workforce training programmes.

The US DoD described in its announcement statement the need for the new institute: "The use of robotics is already present in manufacturing environments, but today's robots are typically expensive, singularly purposed, challenging to reprogram, and require isolation from humans for safety. Robotics are increasingly necessary to achieve the level of precision required for defense and other industrial manufacturing needs, but the capital cost and complexity of use often limits small to mid-size manufacturers from utilizing the technology. The ARM Institute's mission therefore is to create and then deploy robotic technology by integrating the diverse collection of industry practices and institutional knowledge across many disciplines – sensor technologies, end-effector development, software and artificial intelligence, materials science, human and machine behavior modeling, and quality assurance – to realize the promises of a robust manufacturing innovation ecosystem. Technologies ripe for significant evolution within the ARM Institute include, but are not limited to, collaborative robotics, robot control (learning, adaptation, and repurposing), dexterous manipulation, autonomous navigation and mobility, perception and sensing, and testing, verification, and validation." (US DoD, 2017).

The US DoD characterised the current domestic capabilities in manufacturing robotics technology as "fragmented," citing a need for better organisation and collaboration to better position the United States for the global competition in this sector.

An additional Department of Commerce institute, bringing the total to 15, could be developed since NIST's topic selection process had been completed, but the final selection process was subject to the availability of 2017 funds.

The institutes have already been hard at work. The administration has proffered a series of examples on what the institutes have been accomplishing (The White House, 2016):

- To help anchor production of new semiconductor technologies in the United States and accelerate the commercialisation of advanced power electronics, in March, the Power America Manufacturing Innovation Institute successfully partnered with X-FAB in Lubbock, TX, to upgrade a USD 100 million foundry to produce cost-competitive, nextgeneration wide bandgap semiconductors, enabling new business opportunities to sustain hundreds of jobs.
- Using next-generation metals manufacturing techniques, Lightweight Innovations for Tomorrow (LIFT), the Detroit institute focused on lightweight metals, has successfully demonstrated how to reduce the weight of core metal parts found in cars and trucks. A reduction of 40% has been achieved, potentially improving fuel efficiency and saving on fuel costs. In addition, LIFT has introduced curriculum in 22 states to train workers on the use of lightweight metals. In the summer of 2016, 38 companies hosted students in paid manufacturing internships, in partnership with LIFT.
- America Makes has attracted hundreds of millions of dollars in new manufacturing investment to its region. This has included helping to attract General Electric's new USD 32 million global 3D printing hub and spurring Alcoa to invest USD 60 million in its New Kensington, Pa. facilities. Both of these investments will benefit from proximity to America Makes and its expertise in 3D printing with metal powders.
- In addition, America Makes, with Deloitte and other partners, has created a free online course on the fundamentals of 3D printing for businesses. Over the last year, over 14 000 business leaders have taken this course to learn what 3D printing can do for their businesses.

Deloitte, commissioned by DoD Mantech, undertook an independent assessment of the institute model in 2016. Its overall findings, released in a January 2017 report, were quite positive (Deloitte, Manufacturing USA, A Third-Party Evaluation of Program Design and Progress, Washington, DC). It found that adoption of advanced manufacturing was critical for progress in the overall domestic economy to improve productivity growth and the trade imbalance, and for job creation. In this regard, the review found that the public-private partnership model of the institutes can create collaborations to improve R&D investment in manufacturing, overcome problems of collective action in the sector, reduce barriers to innovation, enable better access to intellectual property, and cut risk and cost through shared asset access. Concerning technology facilitation, the review found that institutes can play a significant role in de-risking investments in manufacturing R&D, particularly given the pattern of uneven investment between firms of different sizes and in different sectors. Shared advanced equipment, R&D pooling, technology roadmapping and knowledgesharing enabled by the institutes could create significant benefits for industry participants who would be unable to achieve them on their own.

Regarding workforce training, Deloitte found that the institute model could mitigate the talent gap industrial firms now face as they move into advanced manufacturing. Institute workforce programmes included assessments of workforce supply and demand, employee credentialing and certification, and technology-focused training and apprenticeship programmes. It also found significant progress in creating improved ecosystems for production. The portfolio of institutes, both in the range of technology focus areas and geographical reach, was a strength of the system. Their high levels of membership from

different sizes and types of firms was a signal of the initial success of the model. The institutes were also found to be playing a role in strengthening regional economic clusters key to regional growth. The Deloitte report also made a number of programme recommendations, some of which complement the list of institute challenges that appears in this chapter. Overall, the Deloitte review amounted to an early certification from an independent expert source that the institute model was on the right track.